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Foam Glass Insulation from Waste Glass

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FOAM GLASS INSULATION FROM WASTE GLASS

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The objective of this study is to determine if waste glass from municipal waste streams could be used for production of foam glass insulation both in bulk or rigid board form and pellet form. Results of the study showed that water was the best foaming agent for waste glass for micron sized particles to 0.6 cm pellets, while carbon and calcium carbonate yielded better products for larger objects. With foamed pellets available to industry the development of a market will probably take place by logical processes of replacement of part of the market for conventional insulation materials.

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ABSTRACT

Waste glass has proven to be effective for the production of foam glass insulation both in the bulk or rigid board form and pellet form. Many problems, inherent in the use of water, carbon black, and calcium carbonate as the foaming agents, have been identified and many have been solved by various techniques.

The foaming agents were not equally effective for the same-size foamed objects. Water was found to be best suited for micron-sized particles to 0.6 cm pellets, and carbon and CaCO_3 yielded better products for larger objects.

Large amounts of water can be rapidly incorporated into glass by using a sodium hydroxide (NaOH) solution in a heated autoclave. Smaller amounts can be incorporated into the glass by placing pellets formed by adding NaOH to a glass-clay mixture and directly heating in a furnace.

The foaming process with carbon black was examined by analysis of the density, pore size, and open porosity of the foamed piece. Also, the addition of clay made the foam glass less soluble to water.

This report was submitted in fulfillment of Grant No. R800937-02 by the University of Utah under the sponsorship of the Environmental Protection Agency. Work was completed as of August 1975.

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I. CONCLUSIONS

1. Waste glass without any special treatment such as cleaning and color sorting can be used to form a good quality foam glass.
2. The rate determining step of a water-glass reaction is the build-up of the hydroxide ion (OH) concentration on the glass surface.
3. The rate limitations of the build-up of hydroxide ions on the surface can be avoided by placing the glass in an alkaline solution.
4. Acidic solutions reduce the rate of reactions for incorporation of water.
5. Waste glass with water concentrations in excess of 10% by weight can consistently be achieved by autoclaving from 200-275°C in the presence of hydroxide ion in water. The concentration necessary was found to be from 1 to about 10 normal NaOH solution.
6. Two percent water can be incorporated into glass by spraying a 5N solution of NaOH onto 325 mesh glass particles and heating at 200°C for 30 minutes.
7. Water impregnated glass can foam glass particles as small as 177 microns.
8. In order to achieve closed pores throughout the entire foamed body with water as the foaming agent, the piece to be foamed must be small (65 mesh to .64cm) or the temperature must be reduced sufficiently so that foaming will not take place only on the outside. Preheating at 700°C for a few minutes will help make uniform pores.
9. Foamed bodies from .16cm to 5 cm (2 inches) thick can be obtained by using carbon black as the gasifying agent.
10. The pH, surface area, and absorbed gases of a carbon black are of major concern in selecting the optimum carbon black for the gasifying agent.
11. A larger concentration of carbon and/or a reducing atmosphere will yield smaller pore size.
12. Higher temperatures or use of activated carbons yield larger pores.
13. Densities of foamed discs of carbon, clay and glass decrease to a minimum with time at constant temperature and then increase.

Typical minimum densities of .12-.15 g/cc (7.48-9.36 lb/ft³) were achieved. Pore size of .4-.9 mm were common.

14. Pellets of .32-.64 cm (1/8-1/4 inch) diameter can be produced in a rotary kiln by injecting extruded pellets composed of carbon, bentonite, clay and glass mixed with dry clay. The clay is added to prevent the adhesion of the foaming particles to one another and to the furnace. Densities of 3.23g/cc (14.3 lb/ft³) with overall bulk density of 8.5 lb/ft³ were obtained. This pellet has a thin crust.
15. Calcium carbonate can be used to produce a bulk foamed product with .16-.24 g/cc (10-15 lb/ft³) and 1-3 mm pore size. Large amounts of CaCO₃ increase cell size.
16. Milled limestone whose particle size was less than 5μ gave the best results of the carbonate foamed glass.
17. For .32 to 5 cm (1/8 2 inch) size foamed objects carbon, rather than water or CaCO₃, yields the lowest density combined with the lowest open porosity.
18. Clays decrease the solubility of water in glass but it may be necessary to dissolve them into the glass structure to make them effective in decreasing solubility.
19. The market price of foamed waste glass as rigid insulation is lower than other rigid insulation products.
20. The price and quality of foamed waste glass leads to a strong market potential for foamed waste glass as a rigid insulation product.
21. The eleven western states market for foamed waste glass as rigid insulation would be sufficient to sustain two or three 20/ton/day plants.
22. The national market for foamed waste glass as rigid insulation would be sufficient to sustain fourteen 20/ton/day plants.
23. The market potential of foamed waste glass pellets as lightweight concrete aggregate is weak.
24. The eleven western states market for foamed waste glass as a lightweight concrete aggregate would be sufficient to sustain only one 20/ton/day foamed waste glass plant.
25. The national market for foamed glass as a lightweight concrete aggregate would be sufficient to sustain five 20/ton/day glass plants.

II. RECOMMENDATIONS

Small pilot production of foam glass pellets should be initiated. Either carbon or water could be used to obtain low density pellets. With foamed pellets available to industry the development of a market will probably take place by logical processes of replacement of part of the market for perlite.

III. GENERAL INTRODUCTION

The problem of solid waste disposal is becoming more acute each year. Glass, which constitutes approximately six percent⁽¹⁾ of all solid wastes, is one of the few materials that has not been successfully recycled. Annually, as much as twelve million tons of glass are discarded. Unlike other solid wastes, glass presents no threat to the world's natural resources since the major components of glass (silica, limestone and soda ash) are very abundant in nature. Salvage and recycling of all materials, however, offer the only viable, long-range solution to the waste disposal problem.

Urban refuse is composed of metallic, organic and ceramic materials. To make total solid waste recovery feasible and profitable, all three of these fractions must be recovered and used. The metallic and organic fractions are either already valuable and recoverable or can be incinerated to reconvert thermal energy. Ceramics, on the other hand, have defied potential reuse for a variety of reasons. They will not burn, rot, or otherwise disintegrate over a long period of time. Consequently, the currently available methods of disposal are by sanitary land fill or as an aggregate in asphaltic concrete. However, if a new commodity can be manufactured from the waste glass without expensive color sorting, sizing and cleaning, the possibility exists of partially eliminating the problem of disposal and at the same time establishing a profitable new business. Recent research has investigated the feasibility of foaming waste glass for use as a premium grade insulation in industrial and commercial applications.

The process followed by Pittsburgh-Corning, the only producer of foam glass, cannot be used to foam waste glass. Pittsburgh-Corning melts the raw materials, along with an oxidizing agent (a sulfate or sulfites). They add the carbon during the crushing and grinding of the melted glass. During foaming the carbon is slowly oxidized and the sulfate is reduced. The processes involved in this report show that waste glass can be used to form an excellent foamed material without beginning with the raw materials.

Foaming of glass can be achieved only when there is a proper balance between the sintering of glass particles, gas generation from the foaming agent, and the softening of the glass. To have low density, it is necessary to avoid both the collapsing and coarsening of individual pores. Collapsing of pores arises when the viscosity of glass is too low or when there is excess gas available for foaming. Coarsening of pores is a natural consequence of surface tension that drives a porous system to reduce its surface area. The free energy increase of a glass due to pore generation is

$$\Delta F = \gamma \cdot A$$

where: γ = surface tension of glass

A = total interfacial area of pores.

To have a stable foam minimal coarsening should take place at the foaming temperature. The foaming agents used in this study are water, carbon black and CaCO_3 .

IV. WATER AS THE FOAMING AGENT

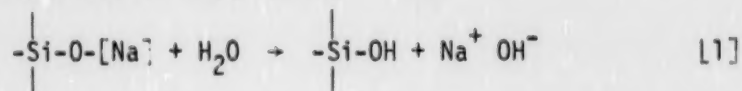
Because gases, such as water, contained in melted glass form bubbles that interfere with the transparency and strength of glass, there has been careful study done by scientists regarding glass manufacturing. These studies have been directed toward processes for eliminating gases dissolved in glass.

An extensive review of the literature describing water in glass has been made by Scholze. ⁽²⁾ From this review it can be concluded that: (1) water is soluble in glass (2) its solubility decreases as temperature increases; (3) water forms hydroxyl groups in glass; (4) water dissolves to form two different types of hydroxyl groups -- one associated with silicon-oxygen-silicon framework and another type of hydroxyl group associated with the sodium ions and other modifier ions. Water solubility in glass can greatly reduce glass viscosity. ⁽³⁾ Combining these concepts one can visualize the incorporation of water into the glass at temperatures below the glass point and then during reheating, drive the water off as steam. As the water escapes from the outside of the glass particle the glass viscosity rises immediately as it returns to its dehydrated initial state. The water trapped inside the more viscous envelope then expands the particle until the surface tension of the glass is in equilibrium with the internal steam pressure.

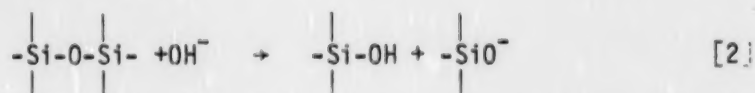
To make the above concept viable for an industrial process, the kinetics and equilibrium water content of glass as a function of water vapor pressure and temperature must be investigated. It has long been

known that water corrodes the surfaces of glasses. Information about the nature of the surface attack and changes in the composition of the corrosive liquid are helpful in evaluating the autoclave process for water absorption.

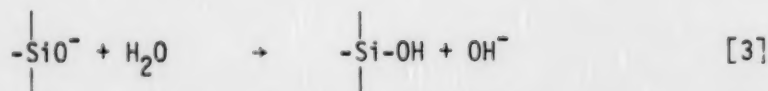
As Charles⁽⁴⁾ reports, when water comes in contact with soda-lime glass the following reaction takes place:



This reaction is a typical hydrolysis reaction. A free hydroxyl ion is formed in the process and the second important step in the glass corrosion takes place as

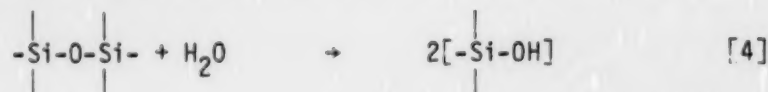


Reaction [2] can occur only after the reaction [1] has already taken place. In reaction [2] the very strong Si-O-Si bond is broken and gives rise to another active group, which is capable of reacting with water as



It should be noted that once a hydroxide ion is formed or is provided, reaction [1] is no longer necessary to propagate the water reaction.

The overall reaction between water and glass may be written as:



These concepts are consistent with the data of Charles⁽⁴⁾ who found that a rather large amount of water could be diffused into glass

at relatively low temperatures and pressures. He followed an interface between the diffused and undiffused volume of the glass. This boundary between the diffused and undiffused region appears to proceed linearly rather than parabolically as would be expected for a diffusion process. Rana and Douglas ⁽⁵⁾ explain that when typical soda-lime-silica glasses react with water the initial rate of reaction varies with the square root of time, suggesting a diffusion-controlled process. Moreover, the activation energy of the reaction is about the same as that for the diffusion of sodium ions in the glass. However, it has been emphasized that this is merely convenient ⁽⁶⁾ and not to be intended as an assessment of the actual mechanism involved.

A. Experimental Procedure

To determine the effect of pressure and temperature on water at various times a single autoclave was used. After receiving a charge of ground glass in steel crucibles, stacked one over the other, the autoclave was sealed, lowered into a Kanthal wound electric furnace and heated to the desired temperature. The amount of water absorbed in the powders was determined. The glass near the top of the crucible was found to contain more water than the glass near the bottom. The glass at the top of the crucible was hard and dense, whereas near the bottom the glass powder was not sintered appreciably. To eliminate the problem, a crucible was made of wire mesh to allow free passage of steam in all cases except for extremely dense sintering. The crucible was hung above the water level so that only steam reacted with the glass powder. Water did not react with the glass in a reproducible manner.

It was reasoned that perhaps water condensation during heat up may be the problem. It was hoped that a twin autoclave system would yield reproducible results because dry steam could be assured and the reaction could be followed from zero time. One autoclave contained the glass sample while the other one contained water. After the test temperature was reached, the steam was allowed to enter the sample autoclave. Of most interest were the experiments at 225°C for several hours. The samples contained only 0.3% water. This aroused the suspicion of Charles ⁽⁴⁾ data.

Seven closed end tubes of soda lime glass and borosilicate glass of o.d. = 8.00 mm to 20.00 mm and i.d. = 5.8 mm to 17.2 mm and 30 cms in length were prepared. Soda-lime glass rods (o.d. = 4.00 mm) were placed inside each one of the tubes. These tubes containing rods were hung with the help of a stand so that the tubes did not touch each other. Each tube was filled with water up to a height of 15 cms and the remaining parts of the tubes and rods were to be in contact with steam. All the tubes were covered with a lid in order to prevent condensed water from entering into the tubes. This package of tubes and rods was placed in a 2.5 liter autoclave which had 400 ml of distilled water to generate steam and to keep the bottom part of the tubes in water. The autoclave was closed and the thermocouple (chromel-alumel) and the pressure gauge were fixed to read the temperature and pressure.

The autoclave was heated in a Kanthal-wound electric furnace and heated to produce saturated steam at 250°C and was maintained for 6 hours. The furnace was shut off and the autoclave was cooled in the

furnace. After cooling, the package of tubes and rods was taken out and the o.d. and i.d. of the reacted rods and tubes were measured at the bottom part which was in contact with water and the top part which was in contact with steam. The observations made and the results obtained are tabulated in Table 1. The measurements were easily made because it was observed that the reacted glass on the surface of the rods and tubes peeled off like flakes, leaving a transparent interior. This was used as the boundary between the reacted and unreacted glass.

The most direct and simple method of determining water content of water reacted glass was to measure weight loss after heating. The reacted glass was dried at 115°C for a long time (≈ 10 hrs). One or two grams of reacted glass were put into a porcelain crucible and weighed before and after. The weight was determined within ± 0.0001 grams on a single pan balance. The glass was then heated slowly to 900°C, maintained for 30 minutes, and slowly cooled to prevent crucible breakage. The crucible and glass were then re-weighed and the difference between the initial and final weighings was assumed to be due to the water being driven off. The amount of water absorbed in the flakes was found to be 9.8% on a dry basis.

Initial foaming experiments were done in one inch diameter crucibles which contained some reacted glass flakes and then put directly into a hot furnace at 900°C and kept for 15 seconds. The flakes expanded or popped to a frothy mass of low density material and the foamed product looked like commercial perlite.

Table 1.
AUTOCLAVE REACTION OF GLASS WITH WATER

Sample Number	Original Size			Water (gm/cm ² of Glass Surface)	Glass Thickness Reacted (mm)			
	Tube		Rod OD(mm)		On OD of Tube		On OD of Rod	
	OD(mm)	ID(mm)			Top	Bottom	Top	Bottom
1	8.0	5.8	4.1	0.0425	0.40	0.00	0.45	0.35
2	9.0	6.6	4.0	0.065	0.40	0.00	0.45	0.10
3	9.9	7.5	4.0	0.0875	0.50	0.00	0.40	0.10
4	11.0	8.6	4.15	0.111	0.40	0.00	0.40	0.10
5	11.8	9.4	4.15	0.131	0.45	0.00	0.45	0.10
6	15.0	12.8	4.20	0.216	0.00	0.00	0.45	0.00
7	20.0	17.2	4.0	0.33	0.00	0.00	0.45	0.00

NOTE: Samples 6 and 7 were pyrex glass. All other glasses were soda-lime-silica.

Common soda-lime glass obtained from crushed clear bottles was used. Although not analyzed specifically, this glass would be expected to have composition similar to the composition of any soda-lime glass. Size reduction of the glass was done by ball milling in a rubber lined mill using steel balls.

In order to determine if sufficient water could be absorbed by glass, the absorption of water was studied as a function of time, temperature, and water in contact with glass powder.

Soda-lime glass powders of -35 + 60 and -100 +200 sieve sizes with 10, 20, 40, 80 and 160% added water (on a dry basis) were reacted at different temperatures. For this purpose glass powders and water were enclosed in small steel bombs (black 3/4" diameter nipple with caps on both sides) and put together in a large autoclave having 400 ml water in it, to avoid any pressure difference between the large autoclave and steel bombs. This arrangement provided good thermal conductivity. The large autoclave containing individual steel bombs was introduced into a preheated furnace and the desired constant temperature was attained in 30 minutes. After heating for the desired time, the furnace was switched off and the autoclave was allowed to cool in the furnace, which took 30 minutes to cool down to 100°C.

After cooling to room temperature the steel bombs were opened and the glass powders were dried for a long time ($\approx$ 10 hours) at 115°C. The reacted water absorbed was found in the same way as in the case of the previous experiment. The percent of water absorbed was calculated on a dry basis. The observations obtained are tabulated in Table 2.

Table 2.

DATA OF WATER ABSORBED AT DIFFERENT TEMPERATURES, TIME AND WATER ADDED

Size	Added Water %	% Water Absorbed (dry basis) at				
		200°C 6 hours	225°C 2 hours	175°C 6 hours	225°C 4 hours	175°C 4 hours
-35 +60	10	1.88	4.12	0.26	5.00	--
	20	2.18	4.50	0.21	5.83	3.79
	40	1.46	0.75	0.21	2.04	7.20
	80	0.51	1.10	0.33	0.76	8.28
	160	0.54	0.94	0.39	0.65	8.07
-100 +200	10	5.57	3.99	2.15		2.01
	20	6.01	4.80	1.26		1.04
	40	2.15	2.28	0.66		0.49
	80	1.10	2.14	0.48		0.40
	160	1.28	1.45	0.38		0.55
						3.42
						4.20
						7.45
						7.76

This is further illustrated in Figures 1 through 5, showing results with glass powders where water content, temperature and time of reaction were variables.

Further to confirm the increased rate of reaction reported by Das and Douglas (7) due to hydroxyl ions concentration, glass powder (-100 +200) was added with 160% water in three different steel bombs. One was left as is, a few drops of sulphuric acid were added to the second and a few drops of NaOH solution were added to the third. All these were autoclaved at 225°C for 6 hours. The water absorbed was found to increase with hydroxyl ion concentration, as shown in Table 3.

The results of Table 3 indicated the importance of high pH in the corrosion process and the need for further study of the effect of alkali. Further experiments were carried out in the same type of steel bombs with different amounts of a one-normal solution of NaOH. The observations are shown in Table 4 and drawn in Figures 6 and 7.

In order to find the minimum concentration of NaOH solution required for the maximum water absorbed, 80% of NaOH solution of different concentrations were added to -35 +60 size glass powder in steel bombs and autoclaved at 225°C for 4 hours. The results obtained are shown in Table 5 and drawn in Figure 8.

The percentage of NaOH solution was then varied with respect to normality and these results are tabulated on Table 6.

With the fact established that NaOH increases the water absorption of glass, it was then necessary to observe in detail the kinetics of the reaction. Glass rods were allowed to react for varying amounts of time and temperature in an autoclave. This data is plotted on

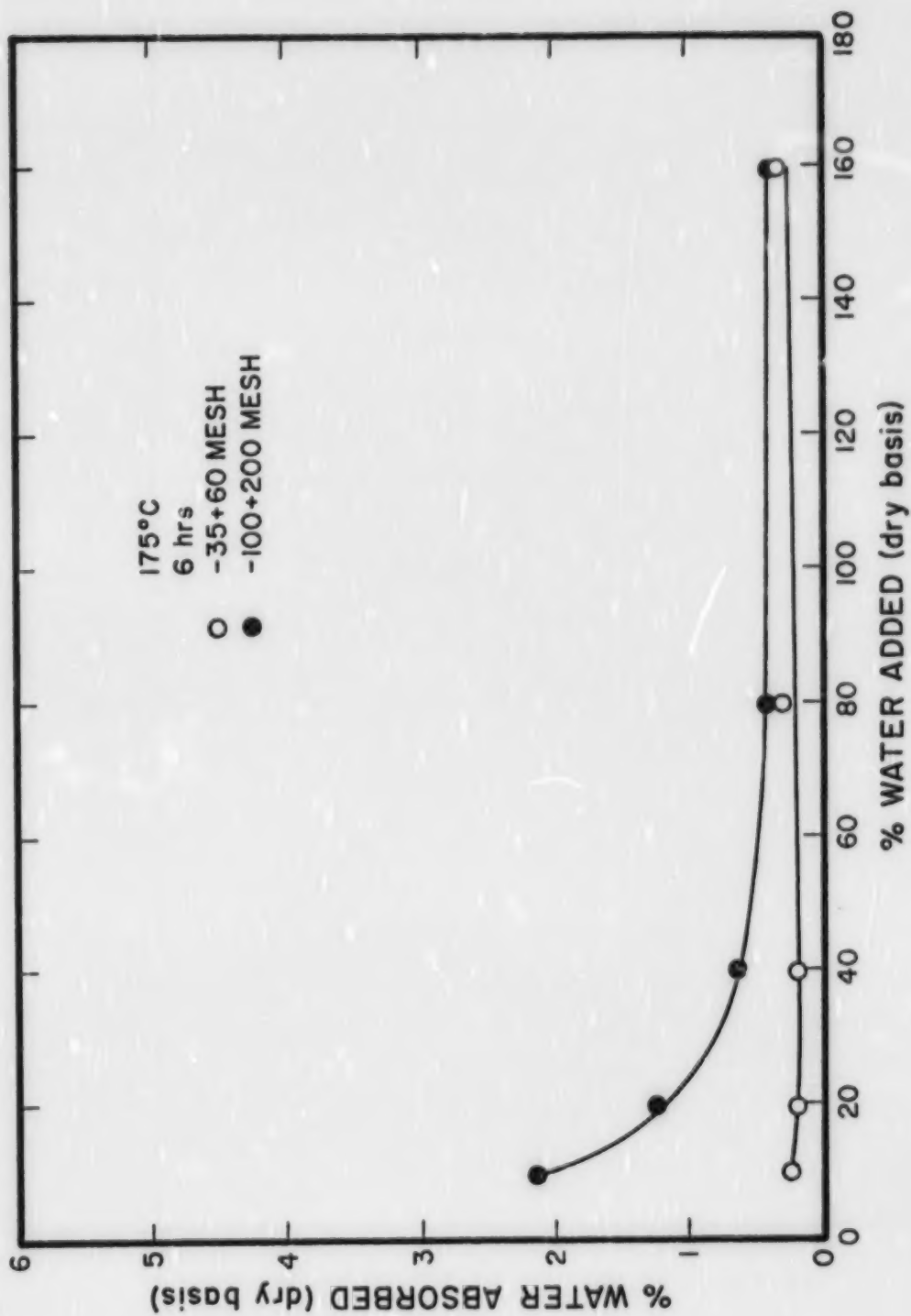


Figure 1. The effect of water content on the water absorbed in the corroded glass at 175°C.

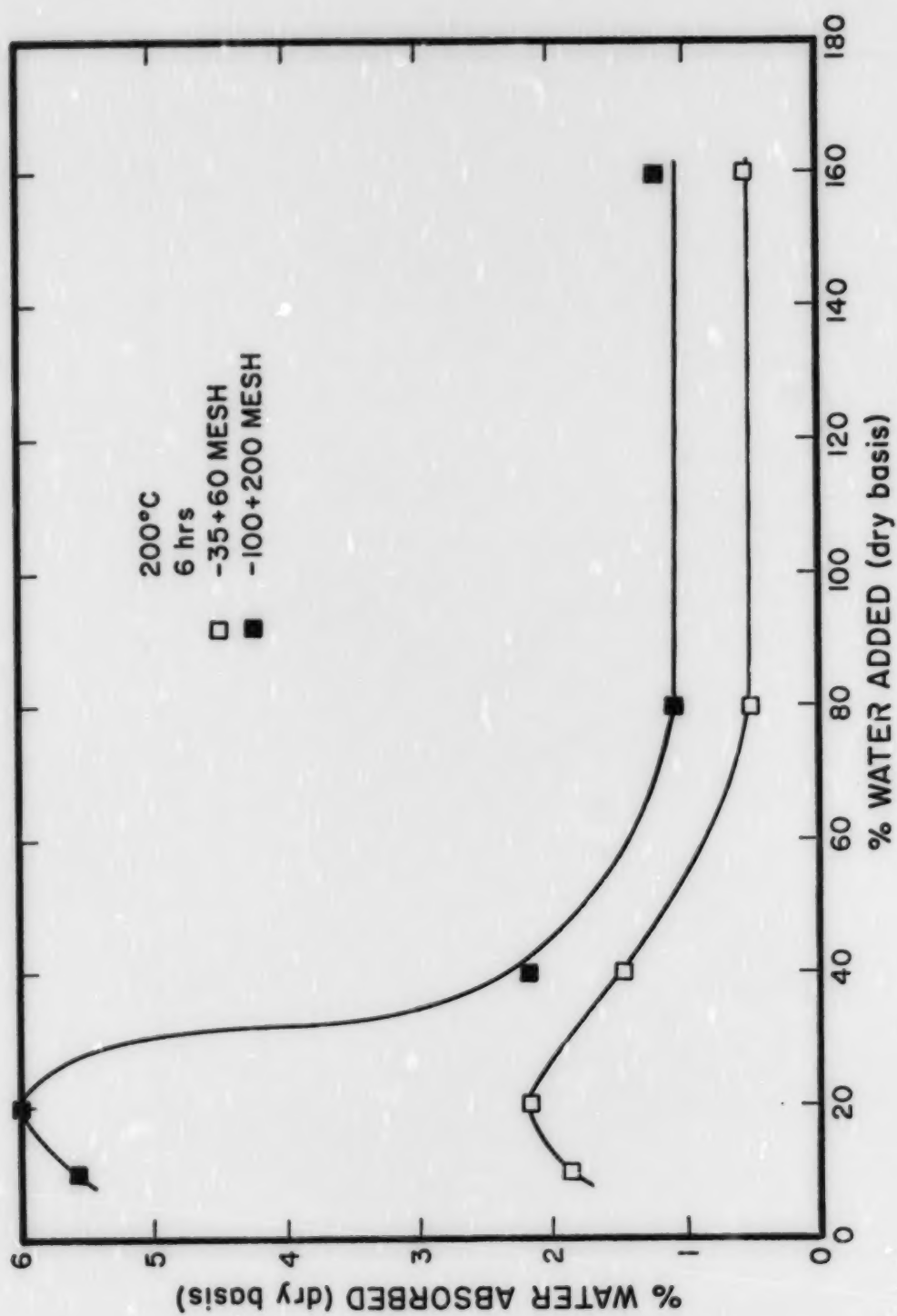


Figure 2. The effect of water content on the water absorbed in the corroded glass at 200°C.

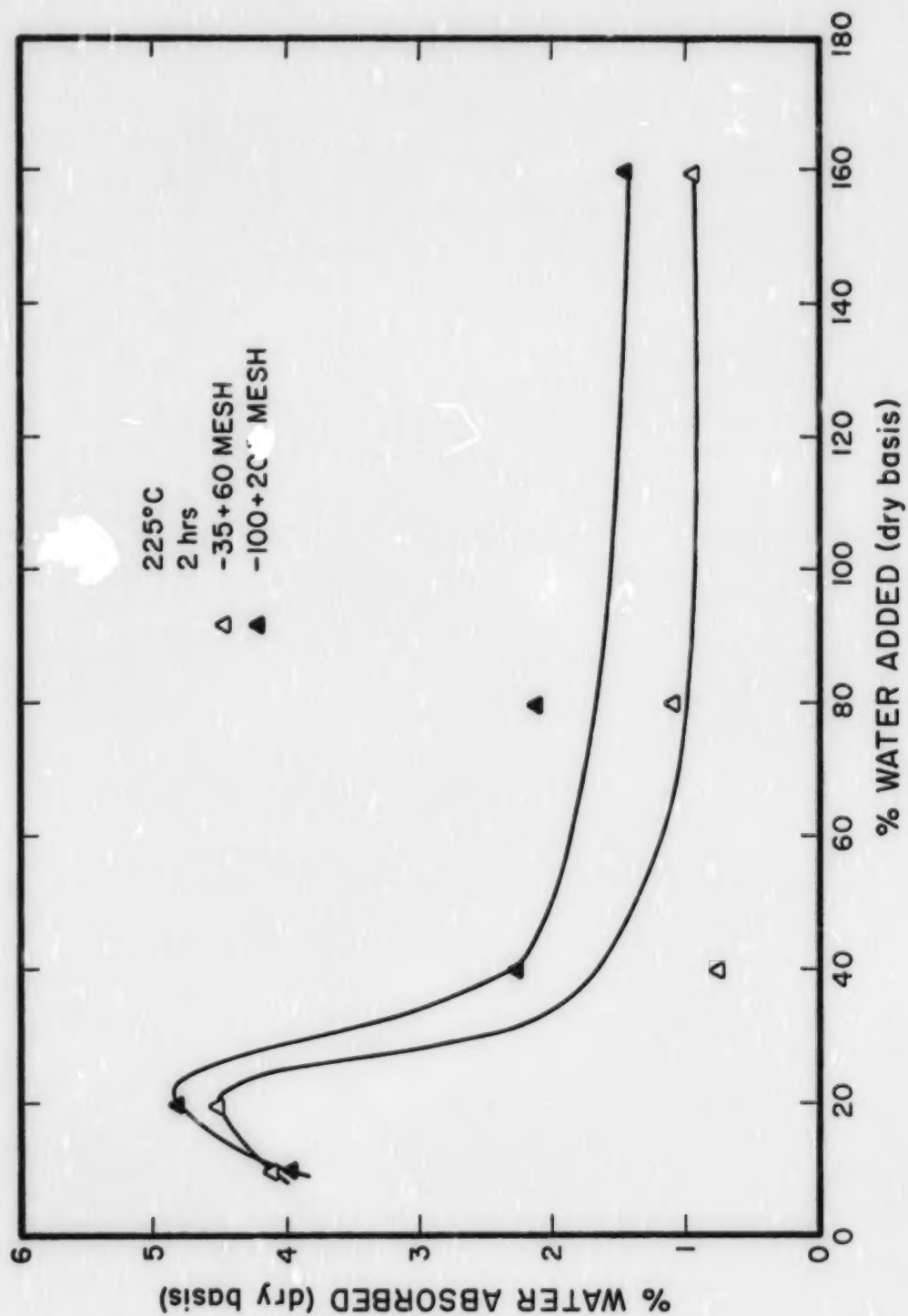


Figure 3. The effect of water content on the water absorbed in the corroded glass at 225°C.

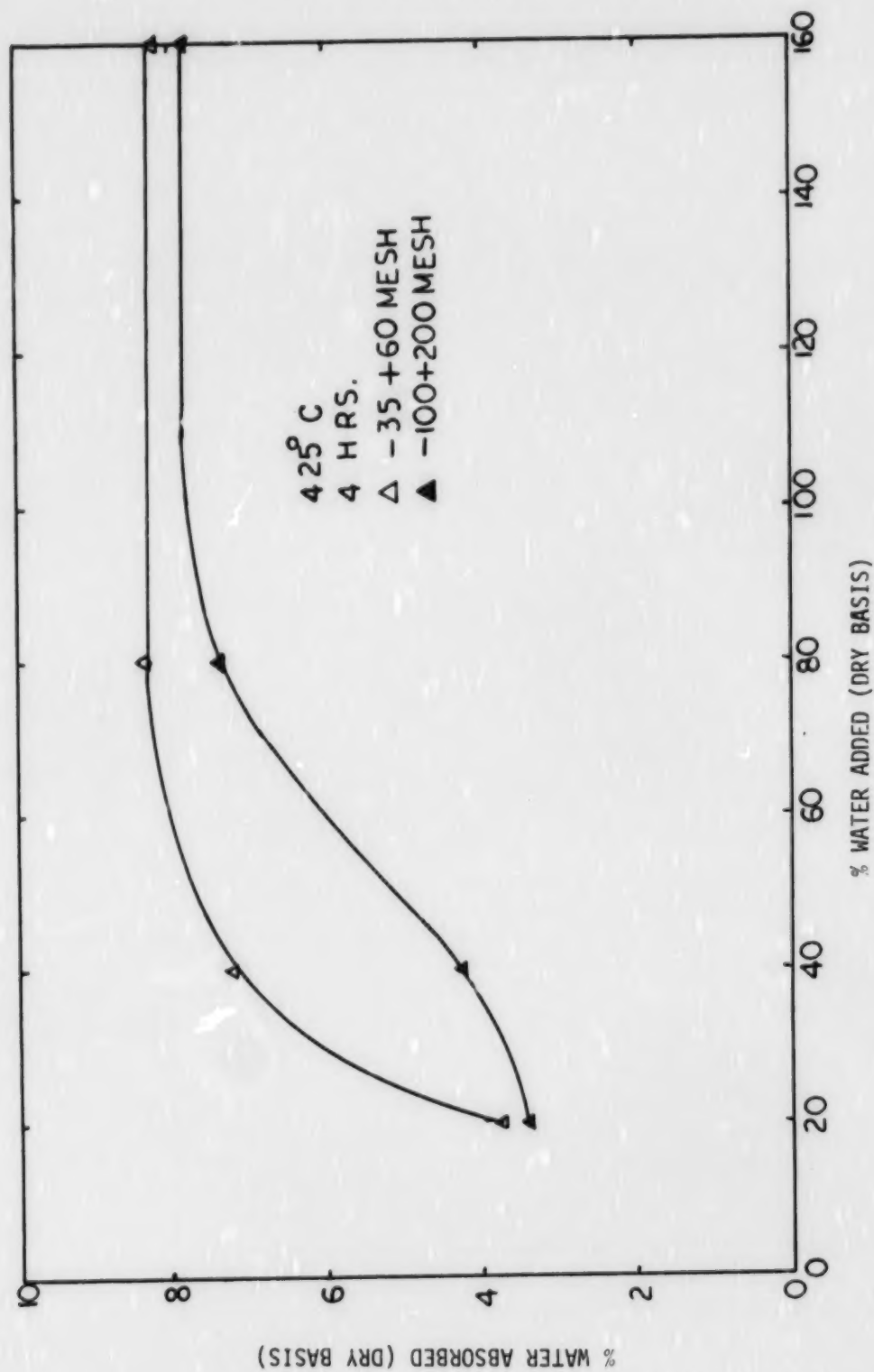


Figure 4. The effect of water content on the water absorbed in the corroded glass at 425°C.

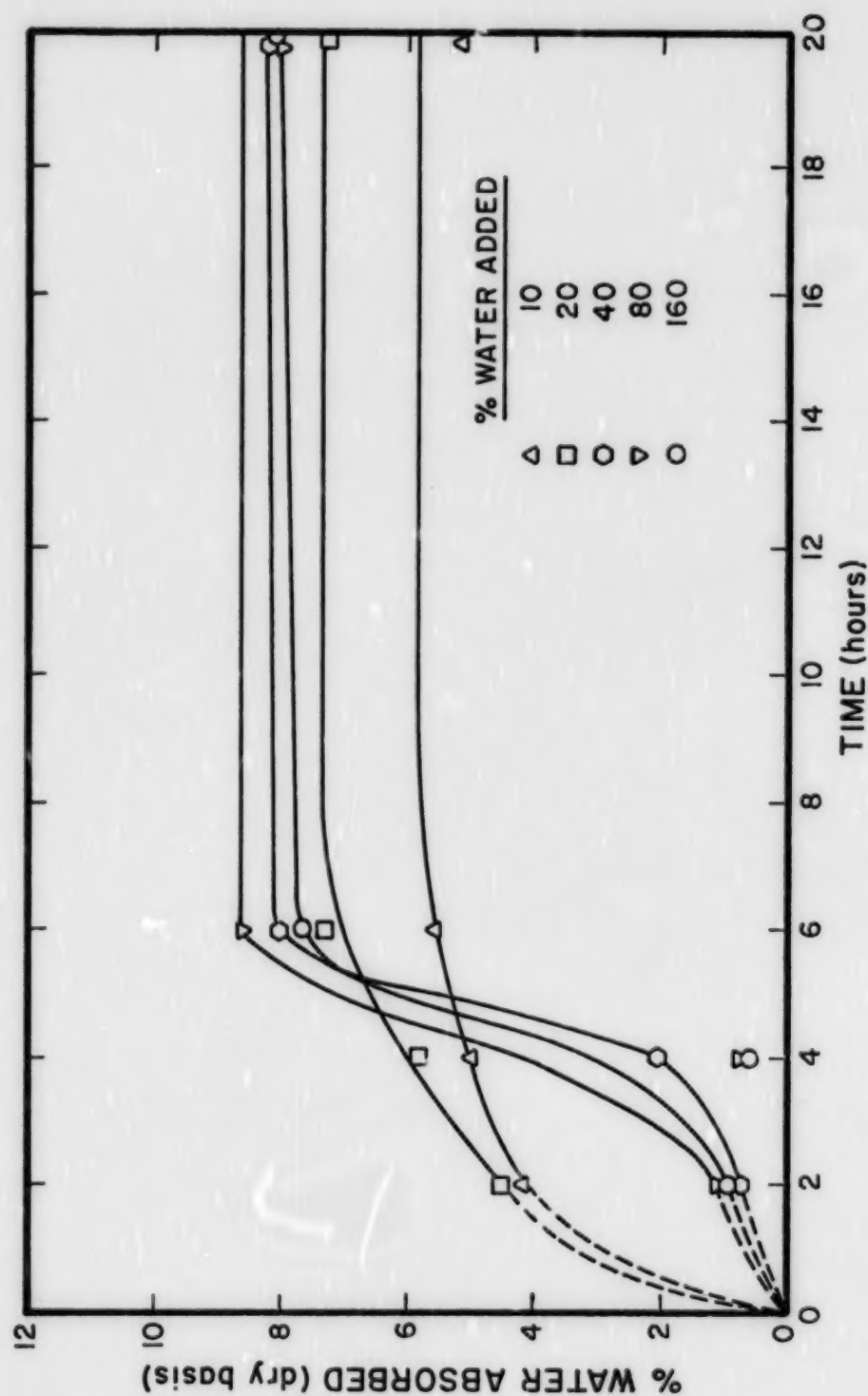


Figure 5. The effect of time and water content on the water absorption of -35 + 60 mesh glass at 225°C in saturated steam.

Table 4.

DATA OF WATER ABSORBED FOR DIFFERENT AMOUNTS
OF WATER AND ONE-NORMAL NAOH SOLUTION ADDED

Water Added	Added 1N-NaOH Solution	% Water Absorbed (dry basis)	
		at 225°C 4 hours -35 +60 size	at 175°C 4 hours -100 +200 size
10	0	5.00	2.01
20	0	5.83	1.04
40	0	2.04	0.49
80	0	0.76	0.40
160	0	0.65	0.55
0	10	6.05	6.14
0	20	9.73	9.87
0	40	10.11	10.54
0	80	10.66	10.32
0	160	10.08	10.86

Table 3.

EFFECT OF HYDROXYL ION CONCENTRATION ON ABSORBED WATER

Added Reagent	H ₂ SO ₄	None	NaOH
% Water Absorbed	2.37	7.70	13.55

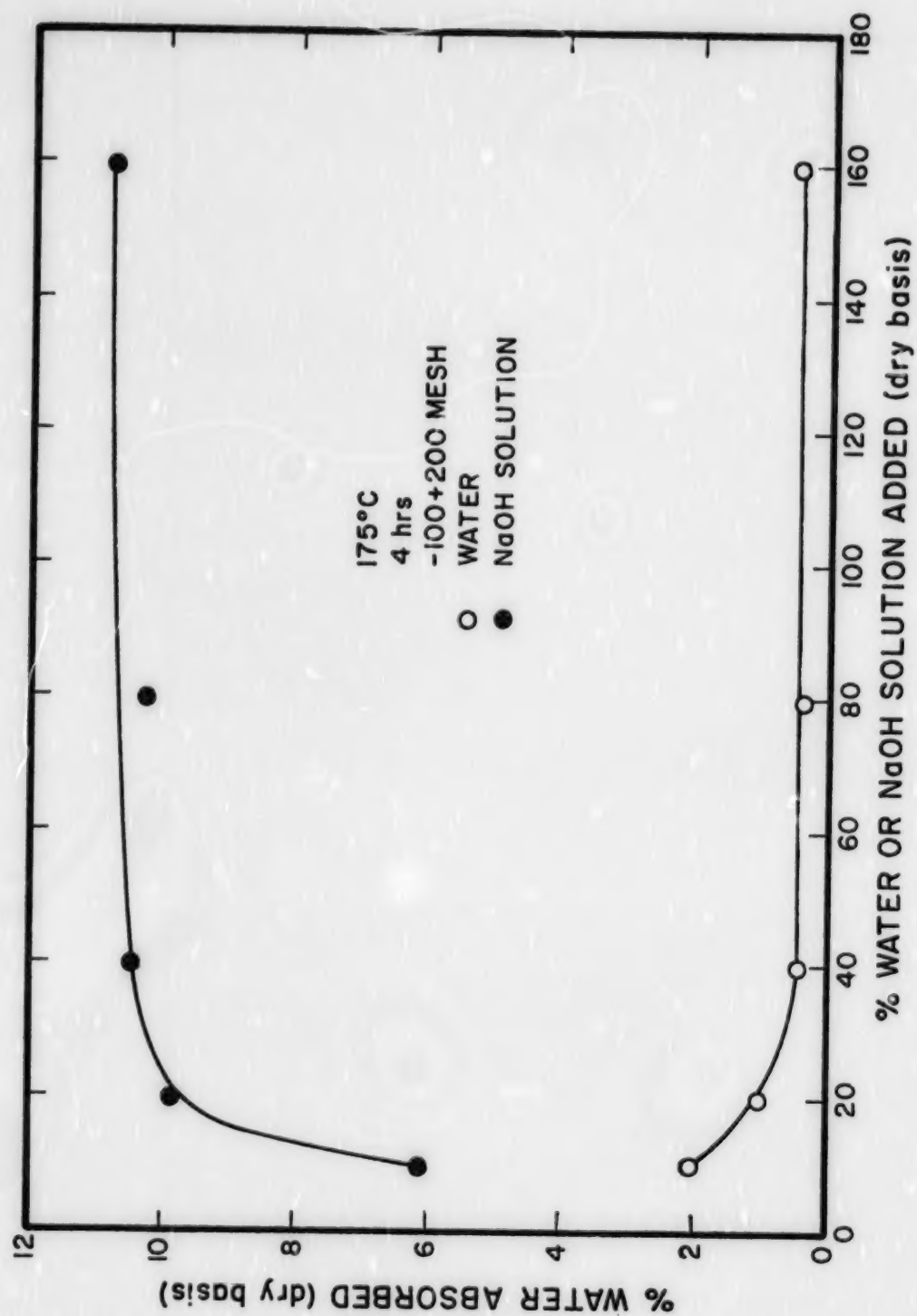


Figure 6. The effect of water or a 1N NaOH solution content on the water absorbed in the corroded glass.

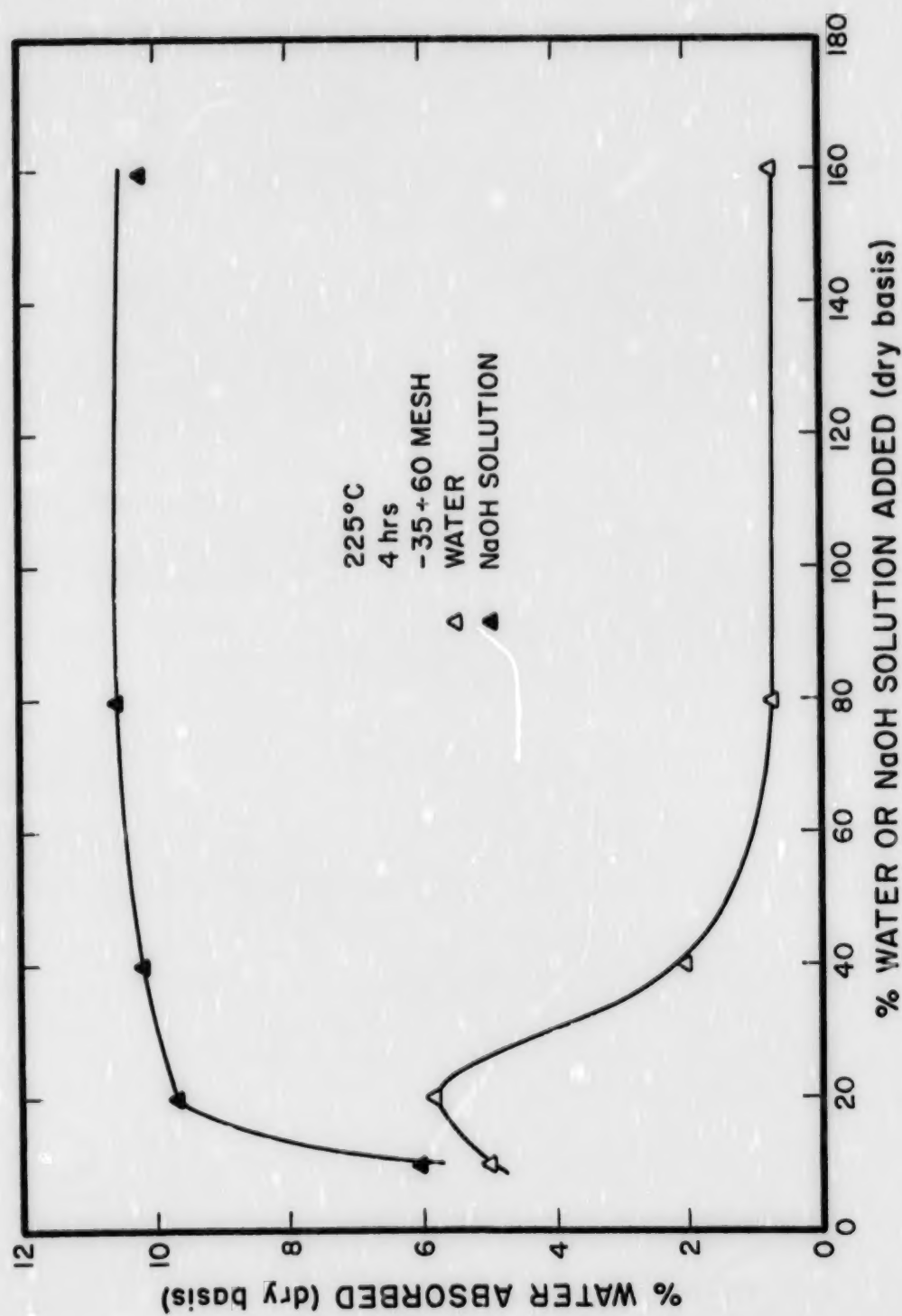


Figure 7. The effect of water or a 1N NaOH solution content on the water absorbed in the corroded glass.

Table 5.

DATA OF WATER ABSORBED FOR DIFFERENT CONCENTRATIONS
OF NAOH SOLUTION

<u>Sample No.</u>	<u>Normality of NaOH Solution</u>	<u>% Water Absorbed (dry basis) at 225°C, 4 hours, in -35 + 60 size when 80% solution added/dry basis</u>
1	0.00	0.768
2	0.05	0.824
3	0.10	0.966
4	0.50	10.91
5	1.00	10.85
6	2.50	14.75
7	5.00	8.48
8	10.00	7.24
9	15.00	6.97
10	20.00	5.98

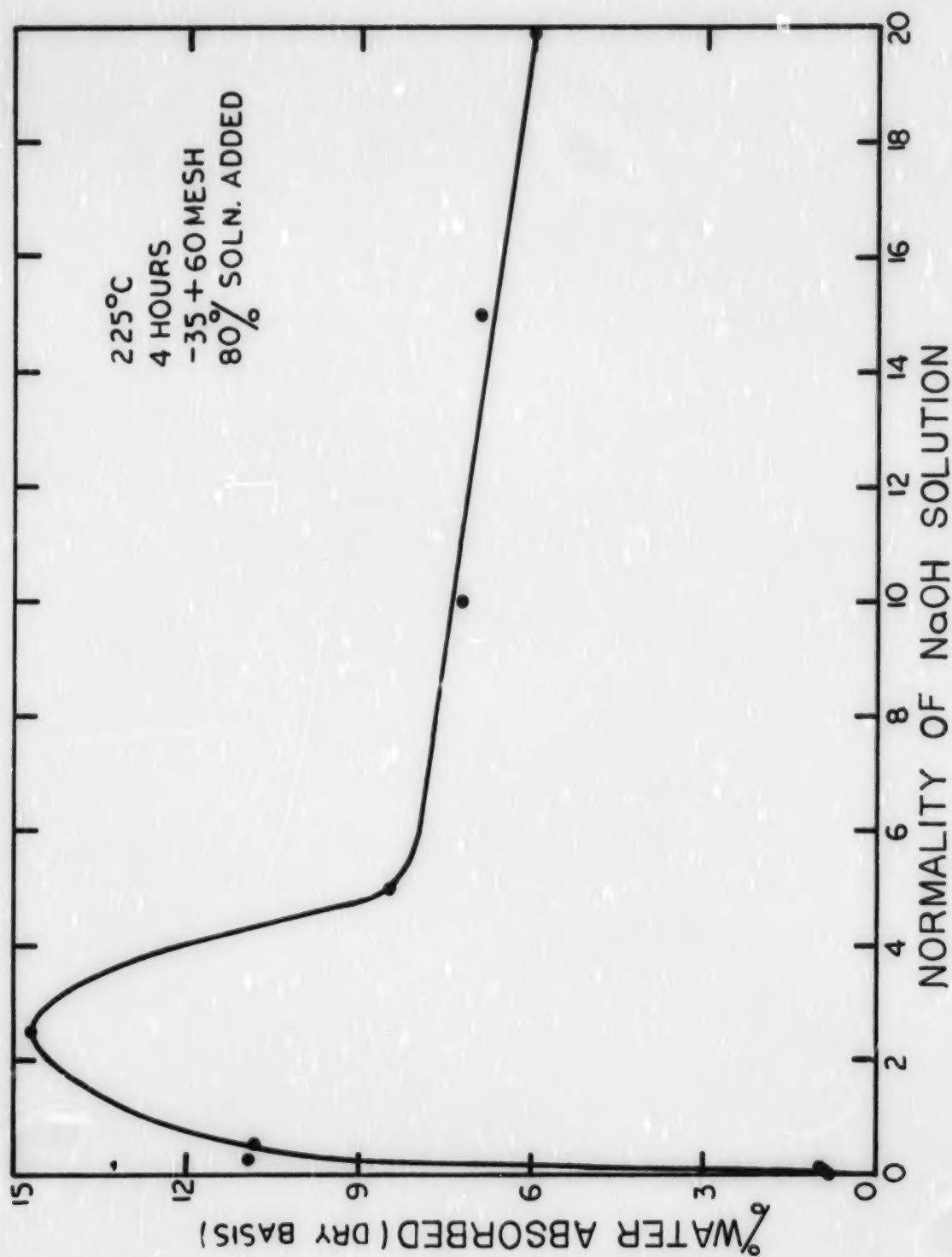


Figure 8. The effect of NaOH concentration on water absorbed.

Table 6.

WATER ABSORBED VS. TIME, TEMPERATURE, AND NaOH CONCENTRATION

Sample No.	Normality NaOH	Solution Added (Dry Basis)	300°C 2 hrs	260°C 2 hrs	225°C 2 hrs	225°C 1 hr	175°C 2 hrs	150°C 1 hr
1	1	40	9.14	10.12	12.80	13.12	14.18	
2	1	80	9.66	10.01	14.24	14.61	23.17	12.3
3	1	160	8.98	9.32	15.23	--	15.38	
4	2	40	9.30	9.82	14.01	16.27	15.37	
5	2	80	9.51	9.52	14.10	12.54	19.74	11.9
6	2	160	9.88	10.23	14.25	--	13.60	
7	4	40	8.34	8.75	15.67	16.19	18.61	
8	4	80	8.30	9.33	20.92	17.30	22.44	
9	4	160	12.27	11.75	7.66	--	14.93	

Figure 9. In order to get the water absorption for shorter times a thermocouple was attached to a steel bomb with -100 + ∞ mesh powdered glass and 80% 5N NaOH solution contained inside. It was lowered into a clay pot in the center of the furnace that was preheated to 200°C. Other bombs were stacked on top of the temperature monitored bomb and removed one by one at the indicated times. As can be seen from Figure 10 the temperature fluctuation of the furnace closely paralleled the water absorption of the glass. The same process was used again but at 150°C and 80% 5N NaOH. This time, in Figure 11, the water absorption rate was much slower. Reaction rate vs. temperature for 5N NaOH catalyzed water-glass reaction is shown in Figure 12. With the activation energy of 20 ± 4 kcal/mole given by R. Charles the time required for the reaction can be determined for a given temperature (Figure 11).

Following this study the glass powder (-100 + ∞ mesh) was autoclaved in 250g quantities contained in tin cans or carbon cloth. These powders, during autoclaving would settle out and form a hard compact when 100% solution was used (a 200% solution would leave a mushy compact). This compact was broken down into various sized particles -28 to +35 mesh, -35 +48, -48 + 80, -80 + ∞ and -325 + ∞ . These particles were placed separately in a furnace at 900°C to 1000°C and fired for times varying from 15 seconds to 90 sec. The particles were also pressed in compacts and fired at 900-1000°C for various times. Large pieces were broken from the compacted mass and fired at different heating schedules. The foaming characteristics were observed.

10 grams type "S" lime composed of 38% Mg (OH), 57%, Ca (OH)₂, 1% MgO was also added to 500 grams of -100 + ∞ glass powder with 500 ml water and autoclaved. The autoclaved glass was then separated into

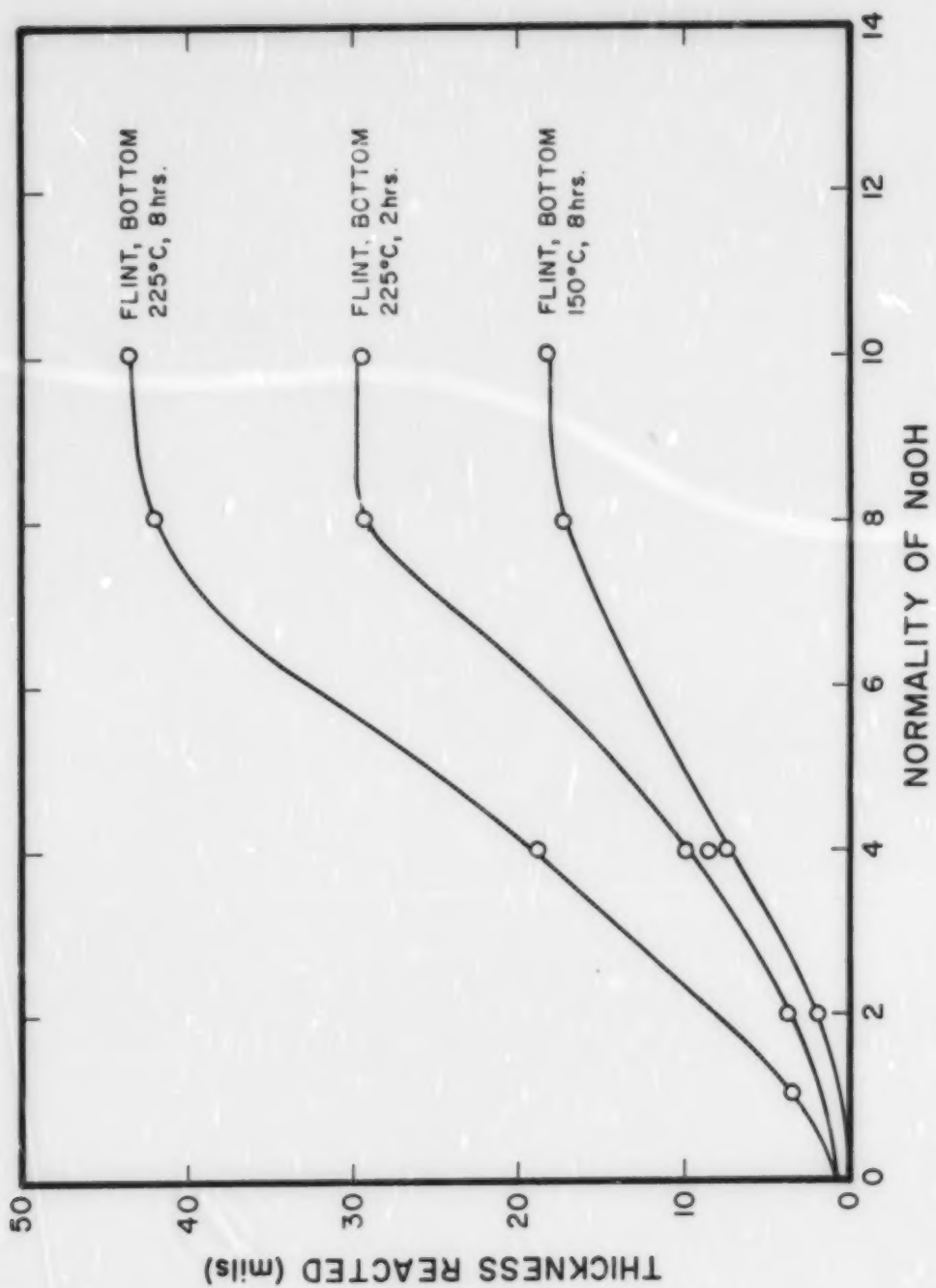


Figure 9. The effect of NaOH concentration on the thickness of the glass rod reacted.

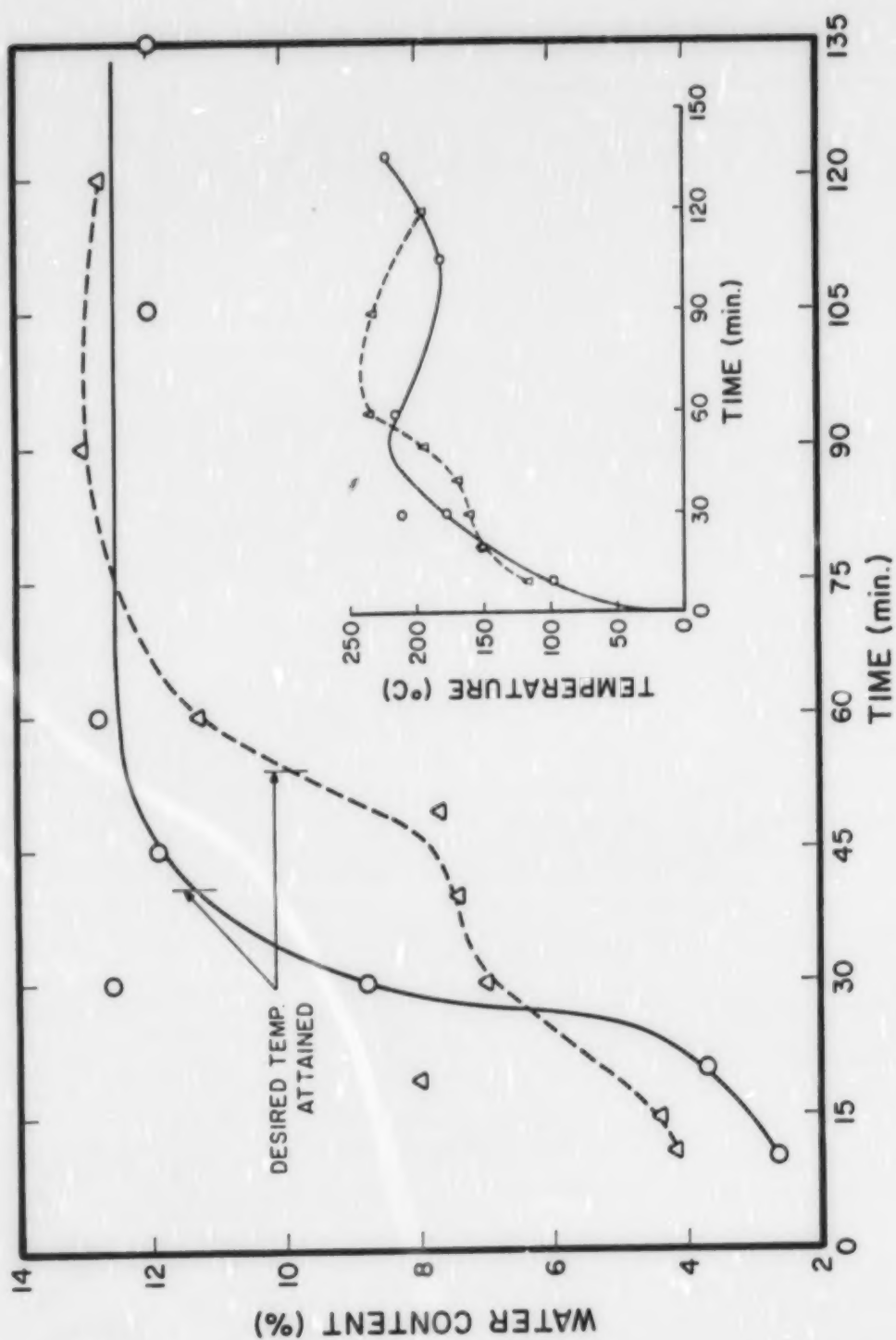


Figure 10. Water absorption of $-100 + \infty$ mesh glass particles autoclaved in a 80% solution of NaOH for various times. The insert shows the temperature variation.

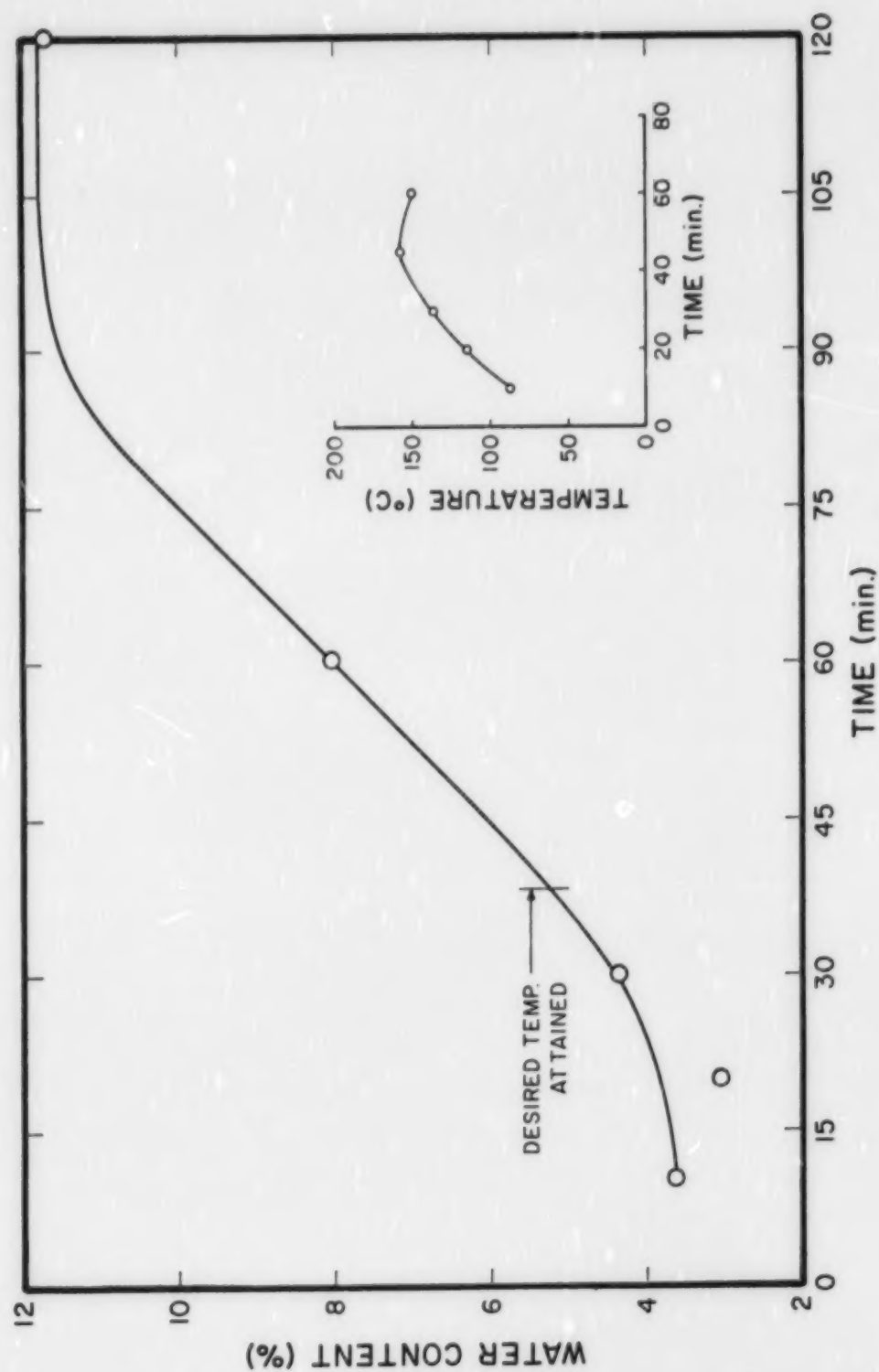


Figure 11. Water absorption of $-100 + \infty$ glass particles autoclaved at 150°C for various times.

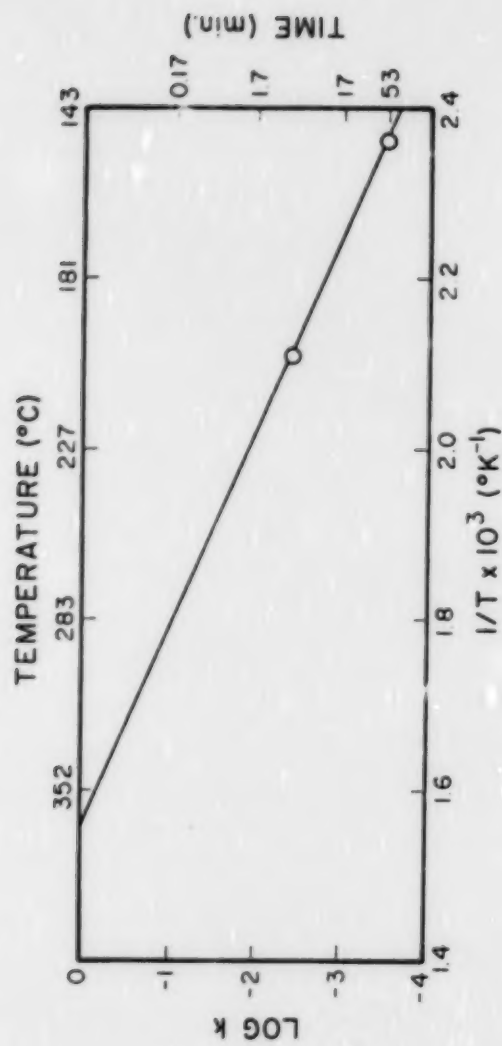


Figure 12. Reaction rate vs. temperature for 5N - NaOH catalyzed water-glass reaction.

small particle sizes. Also, some pellets were formed by squirting a fine mist of 5N solution of NaOH into a rotating mixer which contained 250gm of 325 mesh glass powder and 4% bentonite. The pellets rolled themselves into various sizes. These pellets were put into an aluminum foil container inside the autoclave with 350 ml of water and heated to 200°C. The autoclave was allowed to cool overnight. The samples were then fired at 900°C which gave uniform pores. At 1000°C uneven pore size distribution was evident.

Because such a small amount of water was placed in the bottom of the autoclave, serious thought was taken that perhaps not all the pressure or water vapor was needed. The pellets were made as before but this time they were placed directly into a 200°C furnace for 1/2 hr to allow the water-glass reaction to take place. Then they were fired at varying temperatures and times. Pellets were also produced by extrusion but had poorer quality.

B. Results and Discussion

A range of temperatures and pressures would have been investigated but discouraging results in foaming the product brought the experiments to a narrow range of temperatures restricted to low temperatures by sintering and diffusion constraints. The glass particles begin to sinter at about 600°C under normal conditions. Sintering during reaction with water is undesirable because of the associated reduction in surface area. Therefore, maximum allowable temperatures were of the order of 250°C in a water vapor atmosphere because of the sintering enhancement due to water vapor.⁽³⁾ Below 175°C the diffusion time became increasingly longer.

The results in Table 1 confirm the data of Charles that the glass reacts faster in steam than in water at the same temperature and pressure. The penetration rate was also equal to that given by Charles. Initial penetration or surface layer formation took approximately 2 hours to form a 25 μm thick layer and then in the second stage 425 μm is reacted in 4 hours, which corresponds well with Charles' 120 $\mu\text{m/hr}$ at 250°C in saturated steam.

The higher rate of reaction in the glass/vapor phase is explained by Charles as due to a pH increase at glass/vapor interface in contrast to a dilution of pH at the liquid/glass interface. Higher concentration of hydroxyl ions at the vapor/glass interface break silica network bonding according to reaction [2]. As the corrosion on tube numbers 6 and 7 of pyrex glass (Table 1) leads to the conclusion that dissolution of fused silica and borosilicate glasses in water or steam alone is difficult even at relatively high temperatures. This may be due to the special phase separated structure of these glasses. (8) These glasses have a silica matrix with a very fine (20 to 30 Å diameter) second phase of sodium borosilicate. The matrix or low soda content appears to be resistant to water corrosion by suppression of reaction [1].

The sharp boundary obtained between the reacted and unreacted glass suggests the corrosion reaction can occur at an interface. As the hydroxyl ion concentration builds up, the reaction proceeds more and more rapidly. Kinetically the reaction can be separated into two stages. In the first, the amount of water absorbed or thickness

reacted is proportional to the square root of time, whereas in the second the amount of water absorbed is proportional to time. The rate of the first stage is controlled by interdiffusion of hydrogen and alkali ions, and the second involves a surface reaction.

Table 2 summarizes the data on water absorbed in glass powders at different temperatures with different amounts of water in contact. Figure 1 illustrates the weight gain of glass at 175°C in 6 hours. The weight gain is small and the rate gradually tapers off. Even smaller size powder has absorbed little water, not sufficient to foam the particles. These data demonstrate the importance of higher temperatures, which leads to Figures 2 and 3. At 200°C the water absorbed is about 6% when 20% water is in contact in 6 hours. Still at higher temperatures (225°C) the water absorbed was 5% in only 2 hours, whereas at very high temperatures (425°C) the water absorbed increased to 8% (Figure 4). At high temperatures the solubility limit is probably reached quickly. Increased pressure simply raises that solubility limit. When the temperature is too low, the solubility limit is high but the rate is too slow for equilibrium to be reached in these experiments. It should be noted that rapid corrosion required small water contents, high surface area and, of course, proceeded more rapidly at higher temperatures and pressures. Here the amount of water in contact with glass powder determines the hydroxyl ion concentrations and, consequently, the rate of breaking the silica chains and water absorbed.

The results of Table 3 confirmed the necessity for higher pH for rapid reaction and need for the further study of the effect of alkali concentration in contact with glass powder.

The results of Figures 6 and 7 make it evident that glass reacts faster with water when the hydroxyl ion concentration is high. Glass is more rapidly attacked in alkaline solutions than in neutral or acid solutions because the alkali supplies hydroxyl ions for reaction [2] with the silica network and gives rise to more silanol groups. From Figures 6 and 7 it seems that there is a critical amount of NaOH solution necessary for the highest rate of reaction, above which the rate of reaction becomes constant. Addition of more NaOH solution does not increase water absorption. This may be due to the saturation point reached in the glass structure to accommodate the maximum number of hydroxyl groups.

Glasses react at a very slow rate with acids. Attack of glasses by acids differs from that by water in that any alkali dissolved is neutralized by the acid. Also, the alkali and basic oxide components may be preferentially dissolved, leaving a silica surface layer which reduces the rate of attack with time. Presence of a protective surface film was found by Brueche and Poppa ⁽⁹⁾ having a thickness of $\approx 0.1 \mu$.

Reaction [1] leads to a weakened network through which large ions can rapidly diffuse. The results of Eisenman ⁽¹⁰⁾ are consistent with this requirement, since he found that in the hydrated layer Na^+ diffused only about 5 to 10 times faster than K^+ , whereas in the dry glass the Na^+ is about 1000 times more mobile than K^+ .

This can be explained on the ion-exchange mechanism. As the ion exchange proceeds, the surface layer becomes more open and the water molecule can diffuse in it more rapidly, thus increasing the rate of reaction of water with the silica lattice. Also, the silicon-oxygen

bonds in the surface layer may be more reactive after ion exchange because of the strain resulting from the replacement of a larger ion (Na^+) with a smaller ion (H^+). Therefore, the water-glass reaction is an accelerating process which, at least initially, can be related to Na^+ ion diffusion in the bulk glass.

Figure 8 makes it clear that there is one critical strength of NaOH solution which will allow maximum water to be absorbed in the glass at the highest rate of reaction. Perhaps higher concentration of NaOH solution forms a protective film or stops the Na ion exchange and stops or slows the reaction from going further. In either case, it is quite evident that there is an unreacted core at the center of the glass powders which was confirmed by breaking the particles and looking at the broken pieces under the microscope.

Even higher amount of weight loss of samples 9 and 10 may be due to the NaOH dried up on the surface of the particles, which lost water on heating at 900°C and gained hygroscopic water when kept in atmosphere for a few hours.

Regardless of pressure, temperature, amount of water, or NaOH solution, or size of glass powder, the results were, with minor variation, essentially reproducible.

There are complications to the simple model of water incorporation. No doubt some sodium is leached out, and some of the water, sodium and silica is tied up in crystalline compounds. This is possibly why the activation energies measured by Charles do not correspond to sodium diffusion or glass corrosion energies. From Table 6 it can be seen that varying the NaOH concentration from 1 to 4 Normal along with

varying the amount of the solution, didn't effect the results to any great extent. At 300°C for 2 hours the water absorption was approximately 10%. At 225°C the water absorption was about 14%. It can be seen from this that the temperature of autoclaving has a larger effect than changing normality from 1 to 4 or changing the pressure (1246-psia at 300°C and 343-psia at 225°C).

From Figure 9 it was found that the thickness of the reacted glass increased as the temperature increased as would be expected by rate of reaction control. It is interesting to note that concentrations above 8N NaOH have no additional effect on the rate of reaction. This could be explained by the NaOH forming a protective coat on the glass, or that a saturation point of hydroxide groups that can be accomodated in the glass structure has been reached.

Figure 10 and its insert show that within 15 minutes after the samples reached 200°C the reaction had ended. As the temperature rises and falls so does the water content. This shows how sensitive the reaction is to temperature fluctuations. Since there isn't a wide separation of temperatures involved in the reaction, the rate dependence on temperature should be related as

$$k = Ae^{-E_a/RT}$$

By taking Charles' data that $E_a = 20 \pm$ kcal/mole and $\log k = -E_a/(2.303RT) + A$ the rate of the reaction can be determined. From Figure 11 it is seen that the rate is essentially linear, giving k proportional to $\frac{1}{t}$; where t is the time for the reaction to take place. The reaction time at 150°C in 5N NaOH is 50.25 minutes or 3015 seconds, k then is

proportional to $3.317 \times 10^{-4} \text{sec}^{-1}$. Using this point and the slope of $-20,000/(2.303R)$ a line can be constructed that shows the rate of reaction at various temperatures using 80% of a 5N NaOH solution. This graph appears on Figure 12.

When the autoclaved glass powder with 5-14% water was spaced so that the individual particles didn't touch on a stainless steel tray it was found that glass particles smaller than 80 mesh did not foam. This was probably due to the water being immediately driven from the small particles before a viscous covering could form on the outside of the particle to trap the water closer to the center.

Particles larger than 80 mesh would foam enough to float. The 35 mesh particles produce from 5-7 pores within their structure. After foaming was completed for the differing water content of 5 and 14%, it was observed that there wasn't much difference in the final foamed particles. Autoclaved glass of about 325 mesh size was sprinkled .32 to .64 cm (1/8 - 1/4 inch) deep on a tray and fired at 1000°C. It was observed that it would foam uniformly. When the sample was thicker foaming would begin on the outside and leave a dense inner core. At 850°C powders pressed at 7000psi and .64 cm (1/4 inches) thick didn't foam at all.

The hard sedimented autoclaved glass was also used intact to produce a foam. The autoclaved glass was broken into large pieces and fired. At 850°C a 1.28 cm (1/2 inch) thick piece was fired for 10 minutes and relatively uniform pores of 1 mm were formed. However at 900°C the foaming action was observed to be much more rapid. The density

of .28 g/cc was obtained with an open porosity of 60%. It was noted that even though there were large pores inside, a crust was formed on the outside that made the piece relatively impervious to water.

On further tests it was noted that there was probably too much water absorbed into the glass to give good results and that good foaming would occur on the outside while the inside would remain dense. To verify this, two identical samples were obtained. One was placed into a furnace for 10 minutes at 700°C. Then both samples were placed directly into an 850°C furnace for 7 min. The foamed pieces were observed and noted that the pre-fired sample had 1/2 the pore size of the sample that was not prefired. This could be explained because of the lower water content during the final firing. The density obtained for the prefired sample was .46g/cc.

An autoclaved lime-glass mixture at 200°C yielded a water absorbancy of 12%. This further verifies the fact that the hydroxide ion is a necessary step in the water glass reaction. Small autoclaved glass particles (-35 +48 mesh) would yield foamed particles that would float when fired at 900°C for 30-45 seconds. However, even at higher temperatures a pressed disc wouldn't foam.

When the 5N NaOH mist was used to pelletize .62 cm pellets from glass-clay mixture in the rotary mixer, the water absorption was found to be 12% in the pellets that were autoclaved; while the 5N pellets not autoclaved, but heated to 200°C, had 2% water absorption. It was found that both products would foam. At 850°C the pores of the 12% glass pellets were about twice as large as the 2% with a density of

.29g/cc. The 2% glass had a density of .38g/cc for the same time of 2 min in the furnace. The crust of the 2% glass was denser and thicker than the 12%. At 900°C the pores of 12% were smaller than the 2% for the same firing time. The 12% glass had a bulk density of .25g/cc while the 2% had a density of .44g/cc. The reason the pores of the 12% absorbed water were smaller than the 2% is that glass at higher water content is less viscous at a given temperature which would make smaller pore stabilization possible. A possible explanation for the 2% glass increasing in density at higher temperatures while the 12% does not is that a greater proportion of the 2% water is removed from the glass before the sintering mechanism can trap very large amounts of the water at higher temperatures. A large amount of the 12% water in the glass could escape but a large amount of water would remain to foam the glass. With lowered viscosity and more foaming agent, a less dense particle is produced from the 12% water reacted glass than the 2% at higher temperatures.

A large pellet from the autoclaved sample with 12% absorbed water was prepared by squirting a 5N NaOH solution, whose final foamed dimension was 5 cm when fired at 900°C. A density of .14g/cc with uniform pores was obtained. However, a high water absorption into the foamed object was 64%.

From this data it is evident that more than enough water can be put into the glass to foam it and that foaming of very small particles is possible when using water as the foaming agent. For large objects it appears that pelletizing in a rotary mixer before autoclaving will yield the best results for pore uniformity and density, although high

in open porosity as compared to sedimented compacts which require closer temperature controls.

Pellets were also extruded but the foam produced after firing was coarser and less uniform. This confirms the tendency obtained throughout, that the best results come from the most loosely packed mixture. These loosely packed structures probably allow more of the gases to escape before sintering begins and the foaming is more controllable due to the smaller amounts of the vapor.

V. CARBON AS THE FOAMING AGENT

The carbon foaming process is largely dependent on the type of carbon that is used. Carbon blacks available on the market today are very diverse in their individual characteristics. The carbon blacks examined as the foaming agent were the furnace blacks, channel blacks and activated carbons. These carbons differ by the manner in which they were produced. The activated carbons are carbons that were deposited at low temperature and are free from absorbed and stabilized hydrocarbons on their surfaces. Furnace blacks have oxygen contents below 1.5% while channel blacks have between 3-4% oxygen.

Carbon black particles have extensive surface areas. Surface areas ranging from $25 \text{ m}^2/\text{g}$ to $1000 \text{ m}^2/\text{g}$ were studied. This large surface area is due to the interconnecting pores which permeate the particle. However, it has been observed that the most porous carbon doesn't necessarily absorb the largest amount of gas. It has been proposed from this that the pores should be about the same size as the absorbed gas molecules. There is some evidence that the gases absorbed are condensed into a liquid. When gases are absorbed onto the carbon heat is evolved. The heat of absorption of CO_2 is 6800-7800 g cal/mole while the heat of liquifaction is 6250 g cal/mole. (11) In addition to this Melscherlick, according to Mantel (12) observed that CO_2 , at 12°C and atmospheric pressure, was absorbed into the carbon and occupied 1/56 its initial volume. This being the case, there could be large volumes of gas on the surface of the carbon.

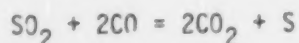
In addition to the absorbed gases there are other elements that are chemically bound to the carbon. It has been shown that the carbon black contains .2-1% hydrogen, .1-4% oxygen and up to 1% sulphur.⁽¹³⁾ The reason hydrogen is present is because the carbon black is generally made from hydrocarbons. Oxygen appears from the oxidation of the hydrocarbons.

Table 7 shows that the various carbons have different pH values. This is due primarily to the carbon dioxide which is chemically or quasi-chemically bonded to the surface due to oxidation. With increasing CO₂-complex concentration more surface ionization results, giving a larger H⁺ ion concentration. Other functional groups such as quinone and phenolic groups have been identified. With these acid radicals present, the carbons become more hydrophilic.

As the carbons are heated to the 850° range several changes can take place. One of these is the evolution of the absorbed gas. With increasing temperature, carbon dioxide comes off first, followed by carbon monoxide, hydrogen, and if present, sulphur dioxide. Sulphur dioxide can react in the following manner



or under a carbon monoxide atmosphere



The second reaction is important since 1 less mole of gaseous products are formed than is reacted. This would mean that when the SO₂ and CO₃ were desorbed they would react to give 1 less mole of CO₂, thus decreasing the volume of gas effectively evolved.

Table 7.
CARBON BLACKS EXAMINED FOR FOAMING GLASS

<u>Carbon Black</u>	<u>Carbon Type</u>	<u>Particle Size um</u>	<u>Surface Area m²/gm</u>	<u>pH</u>	<u>Fixed Carbon</u>
1. Continex F-1	F	80	25	8	98.5
2. S-315	F	.0280*	89	3	--
3. N-330	F	.0798*	--	8.2	--
4. P-108	Act.	.05-.15*	1000	4-6	--
5. Neo-Spectra 2	C	13	906	3	88
6. Neo-Spectra 4	C	15	335	5	95.8
7. Continex F-3	F	47	42	8	98.5
8. Raveen 2000	F	17	235	9	97.8
9. Raveen 1040	F	29	85	3	96.5
10. Raveen 14	LB	--	--	--	--
11. Raveen 3500	F	16	319	3	96.2
12. HAF #4	F	--	81	--	--
13. Raveen 1255	F	22	130	3	96.1
14. U-3024-L	F	50	34	8.5	99.0
15. XZ (Nutshell)	Act.	98%thru*			
16. NW (Hardwood)	Act.	95%thru*			
17. YD (Nutshell)	Act.	90%thru**		Basic	
18. 410 (Nutshell)	Act.	70%thru**		"	
19. JF (Nutshell)	Act.	.20<x<.40***			

F - Furnace Black

C - Channel Black

LB- Lamp Black

Act. - Activated Carbon

*325-mesh residue

**200-mesh residue

***250-mesh residue

The carbon with its absorbed gases can be mixed with glass particles. At 850°C the particles sinter together and form a viscous liquid surrounding the carbon. The gases evolve from the carbon particle and cause a gaseous pore to develop. As the pores expand they are hindered by contact with another expanding pore; so that the larger the distance between nucleation sites, (carbon particles) the larger will be the pores. The glass-carbon mixture ceases to expand when the gas inside the pores come into equilibrium with the surface tension of the glass.

A. Experimental Procedure

The glass used in these experiments was the ordinary soda-lime glass that was obtained in broken angular pieces from window panes and bottles from a local hospital. These were then crushed in roller mills. The glass was then placed in one-gallon milling drums half filled with large metal balls and allowed to mill for approximately thirty-six hours. This procedure yielded glass particles that would pass through a 325-mesh sieve.

The glass powder was then mixed with standard one-percent bentonite and varying percentages of each carbon in a vibratory mill. The clay was incorporated in this study since it is anticipated that the industrial application would utilize extrusion methods for forming the green piece; it is desired that this study be applicable to the extrusion method.

The glass mixture was pressed initially at 2493 psi, 3739 psi, and 4986 psi. Finally, 2493 psi was chosen to be the standard pressure

because it led to less capping of the compact. The dimensions of the pressed compacts were 3.18 cm (1.25 inches) in diameter and about .94 cm (3/8 inches) high.

A standardizing run was made on all carbons at 850°C with a 1% carbon concentration in a Thermolyne furnace. Two samples were then selected that had thin crusts and uniform pores, and two others which had large pores. These carbons were U-3024-L, F-1, R-1040, and S-315 respectively. Varying compositions were also tried and in all cases the time in the furnace was thirty minutes.

The method employed for firing consisted of pre-heating the furnace to the indicated temperature and placing the pressed compacts into the furnace. After thirty minutes the samples were removed with tongs and allowed to cool under insulation outside the furnace.

The process of foaming was also noted as a function of time, temperature and content. Ten samples were all placed in the preheated furnace (Lindberg) at the same time and removed one at a time at the specified intervals. Observations were recorded for various carbons and density and water absorption measurements were made. The pressed compacts during firing expanded to about 6.36 cm (2 1/2 inches) in diameter. However, because of the crust and a few localized giant pores, caused probably by pressing, it was thought that the density measurements would be best calculated by measuring a selected sample cut out from the middle of the specimen and then weighing this sample. Dividing the weight by the volume of the sample yielded the density. Unfortunately, this method gave results of $\pm .05$ g/cc. Water absorbancy was determined by dry weighing the samples and then placing them in

an apparatus to draw a vacuum. After a vacuum was achieved, water with a little soap to reduce surface tension was allowed to enter the evacuated flask and penetrate all the open pores. The sample was weighed wet to determine the water absorption. This became a measure of the interconnection of the pore space.

Finally, to check the reducing atmosphere effect the compacts were placed in stainless steel beakers and covered by carbon cloth. Care was taken not to restrict the expanding motion of the glass by merely placing the carbon cloth on top so that only the atmosphere effect would enter in.

Following this set of experiments larger samples were foamed and found to be of good quality up to about 2 inches thick.

Pellets were fabricated by extruding a 2% Bentonite, 2% carbon and glass mixture through a .24 cm (3/32 inch) die. These extruded rods were allowed to dry and then chopped up into .32 cm (1/8 inch) lengths. These pellets were mixed with dried ball clay to prevent sticking of the pellets to each other at a 1:2 weight ratio and inserted into a 2 inch diameter stainless steel tube 91 cm (36 inches) long rotating at about 6 RPM through a Kanthal tube furnace on a slope of 2.54 cm (1 inch) per 18 cm (7 linear inches). It took about 15 minutes for the mixture to go through the length of the tube at 850-900°C. The clay was then screened off and used again.

B. Results

After a screening examination of the available carbons, the results of this study were limited to the acid R-1040 and S-315 and the basic F-1 and U-3024-L carbons. The results will be generalized where possible, unless otherwise noted.

It is interesting to note the sequential steps that occur during the foaming operation. Immediately after placing the pressed compact into the preheated furnace the carbon on the sharp corners of the disc immediately oxidizes as evidenced by the whitening of this area. The sintered shell begins to form and reaches its maximum thickness at about eight minutes. The pores then begin forming from the outside in, as evidenced by the larger pores near the shell. As the process continues the gas bubbles make their way to the crust and coalesce, making the pores in the crust larger. Much of the same process is taking place inside. With increasing time the pores coalesce because of the impinging foam surfaces and continued gas generation by the carbon. As this process continues the open porosity increases as shown by the water absorption. During continued heating the carbon disappears, the remaining gases diffuse out, and the foamed compact begins to shrink.

In examining the various influences that exist in the actual foaming; several classifications emerge (1) the factors influencing the formation of small pores (2) the factors governing large pore sizes and (3) the crust formation. These influences are summarized on Table 8.

For small pore formation, an increase of carbon content decreased the pore size, as seen by Figures 13 and 14. It was also noted that many of the samples had significant quantities of absorbed sulphur, since after firing, when a spatula was used to break the foamed piece, an H_2S odor was noted. Since sulfur was available in the

Table 8.

SUMMARY OF FOAMING FACTS

To achieve:

Smaller Pores

1. increase carbon content
2. add desulphurizers
3. use reducing atmosphere

Larger Pores

1. use activated carbons
2. use coal
3. lower carbon content
4. increase temperature

Decrease Crust Thickness

1. cover compact while firing
2. increase carbon content

Increase Crust Thickness

1. add iron oxide

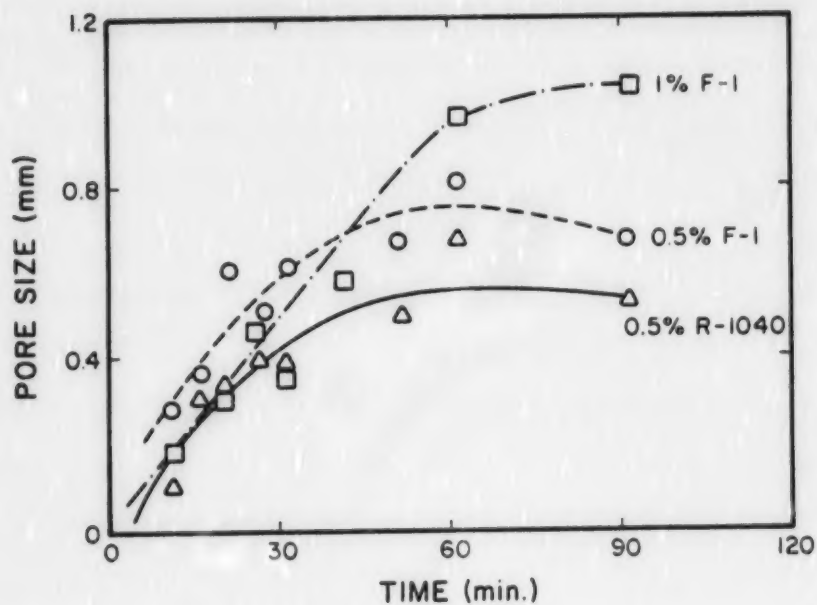


Figure 13. Pore size as a function of time at 850°C.

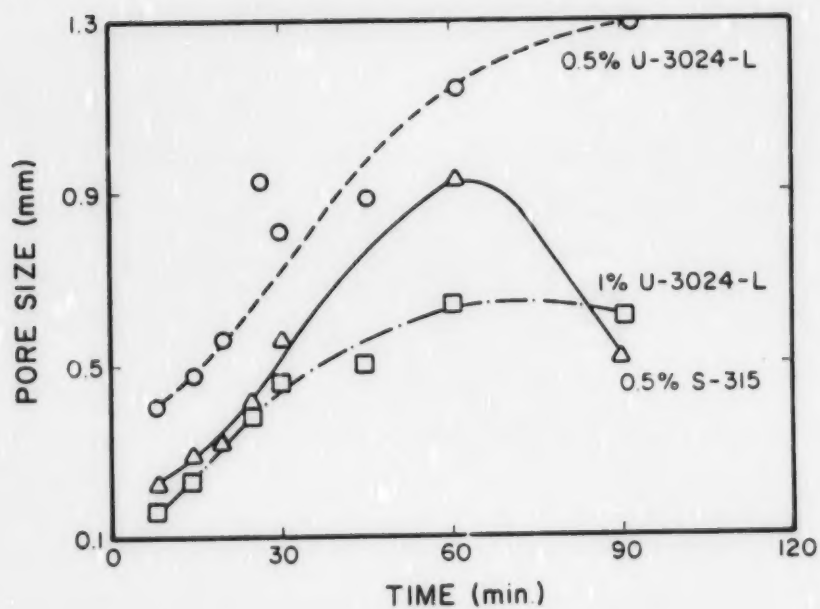


Figure 14. Pore size as a function of time at 850°C.

carbon blacks and in the glass, the exact source is difficult to trace. However, when 1% powdered manganese was added the odor was not present and smaller pores were evidenced. Another factor causing smaller pores was the use of a reducing atmosphere; and in certain instances sulphur was deposited on the container surface. This had the large effect of decreasing the pore size by about a factor of two for the acid and basic carbons considered.

The large pores were generated, in general, by the use of any of the activated carbons. These caused pores to be foamed on the order of 6mm in diameter; as opposed to an average of .6-1mm. Coal also generated large pores. For the carbon blacks tried, it was found that decreasing the carbon content and/or increasing the temperature led to larger pore formation.

The crust or shell of the foamed glass pieces is minimized by covering the sample during firing, increasing the carbon content, or covering the compact with a carbon cloth. It was found that the crust was thickened by addition of powdered iron oxide, and that the R-1040 carbon developed a coherent crust faster than the basic F-1 type. When considering the two basic and the two acidic carbons, the pH seemed to be the largest factor in producing large pore size - the bases being more active than the acids. For a given pH the largest surface area then took effect in producing the larger pore size. When 0.5% acid carbon was used, it was found that it foamed in a general manner comparable to the basic carbons. However, at 1% the acid carbon caused large localized pores with a fine matrix

while the 1% bases foamed much like the 0.5% carbon but with smaller pores at the same temperature.

From Figures 15, 16 and 17 it can be seen that a higher carbon content achieved a lower density than the lower content for a given carbon. The minimum densities range from 0.12-.15 gm/cc. The acidic carbons also have a sharper minimum range and approach minimum density faster than the bases.

As can be seen by the water absorption data from Figure 18, a linear rate of increase for the 0.5% carbons is maintained for the first twenty-five minutes; and except for F-1, the first forty minutes. The rate of water absorption for both acid and basic carbons is 0.1 gm H₂O/ gm sample/min. For the acidic types the water absorbancy reaches its peak at 40-45 minutes and begins to decrease because of the collapsing pore walls.

Figures 13 and 14 show an approximate linear increase in the rate of pore growth for the different carbons in the early stages of foaming. For the 0.5% and 1% variations in carbon, it was seen that the 1% carbon content had a slightly slower rate of pore growth than the 0.5% mixture. The most pronounced effect was in the U-3024-L carbon where the 0.5% rate was about .022 mm/min. and for the 1% it was .013 mm/min. It is possible that the carbon addition has increased the viscosity of the glass.

When the acidic carbons were placed in an aqueous medium the carbon particles were wetted and went into suspension while the basic types remained on the surface. The U-3024-L carbon wouldn't wet

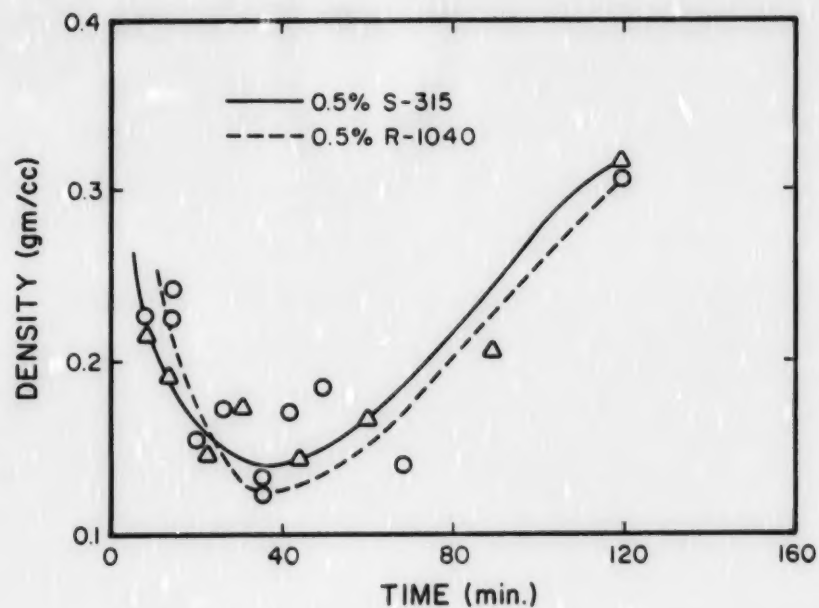


Figure 15. Density as a function of time at 850°C for S-315 and R-1040 carbons.

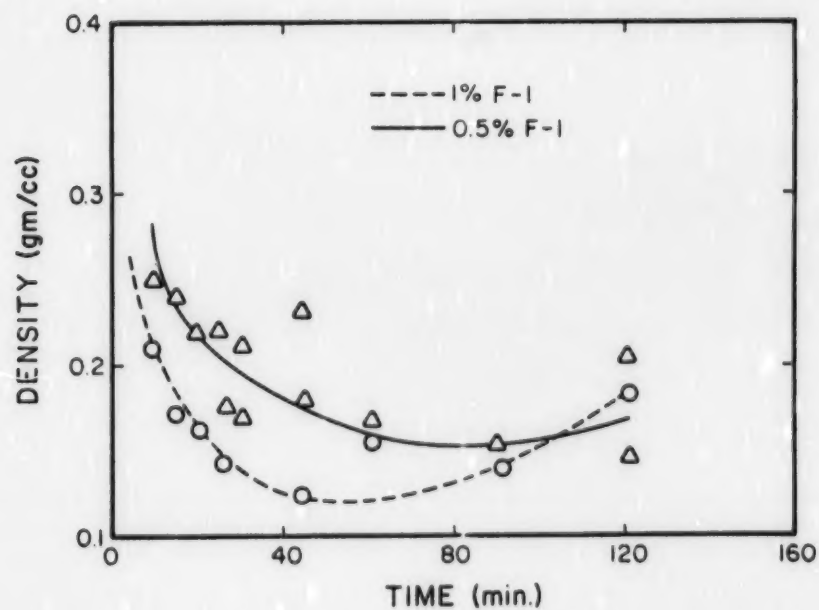


Figure 16. Density as a function of time and carbon concentration at 850°C.

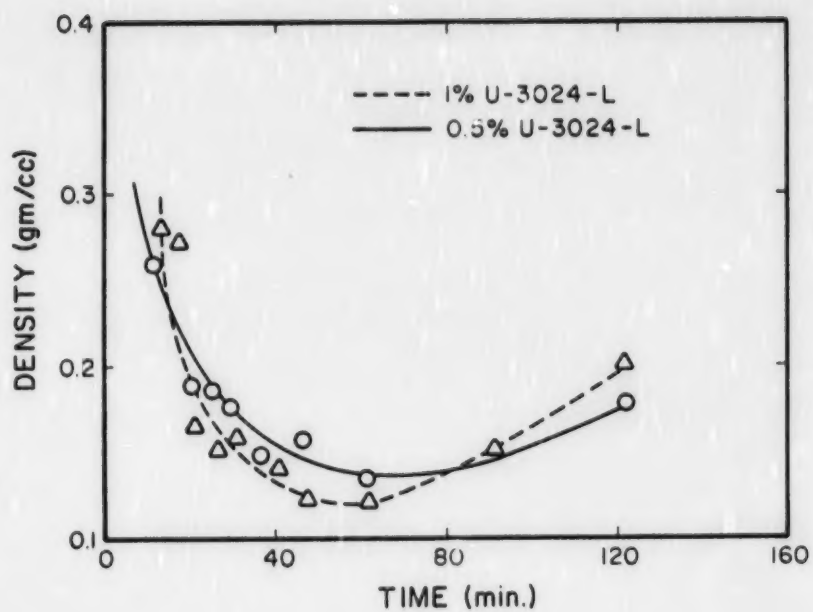


Figure 17. Density as a function of time and carbon concentration at 850°C.

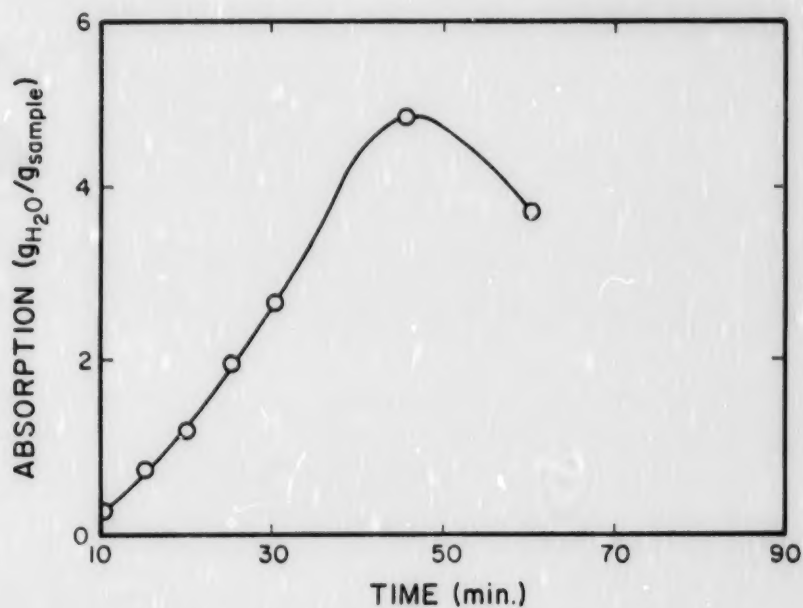


Figure 18a. Water absorption of 0.5% R-1040 carbon black foamed glass as a function of time at 850°C.

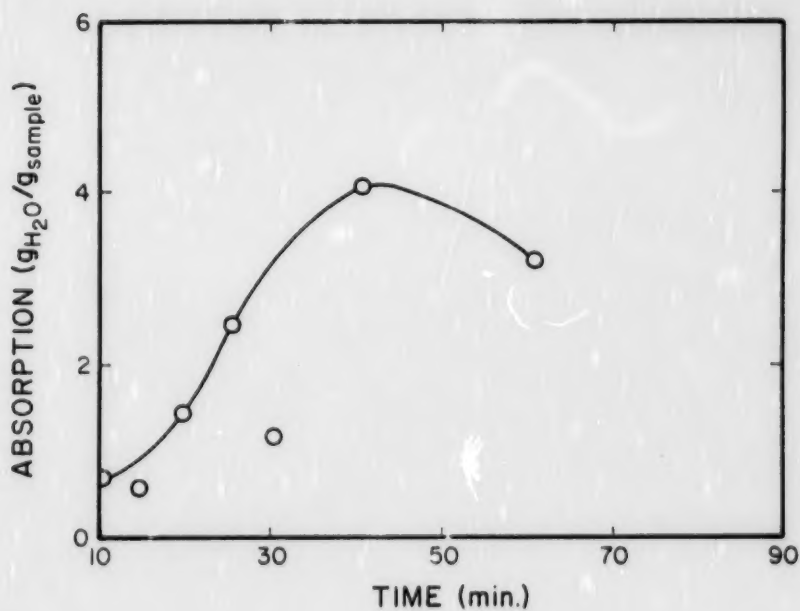


Figure 18b. Water absorption of 0.5% S-315 carbon black foamed glass as a function of time at 850°C.

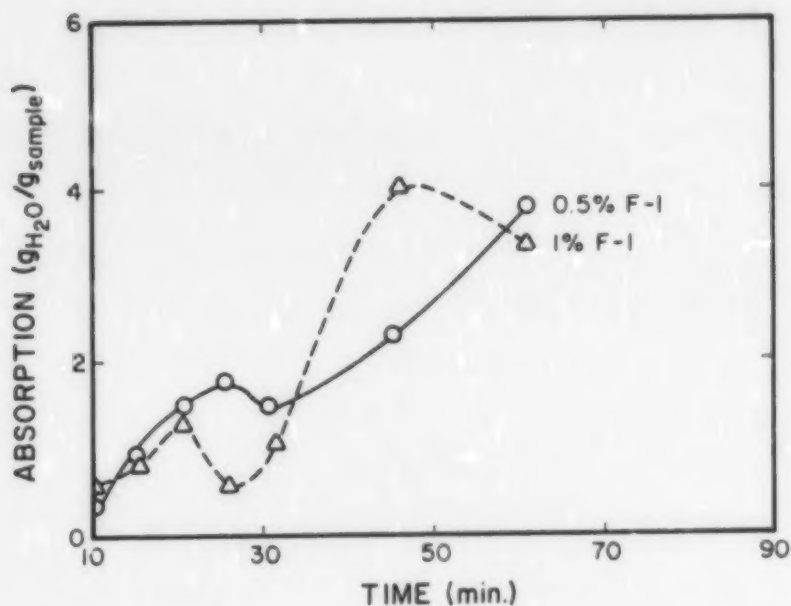


Figure 18c. Water absorption of F-1 carbon black foamed glass as a function of time at 850°C.

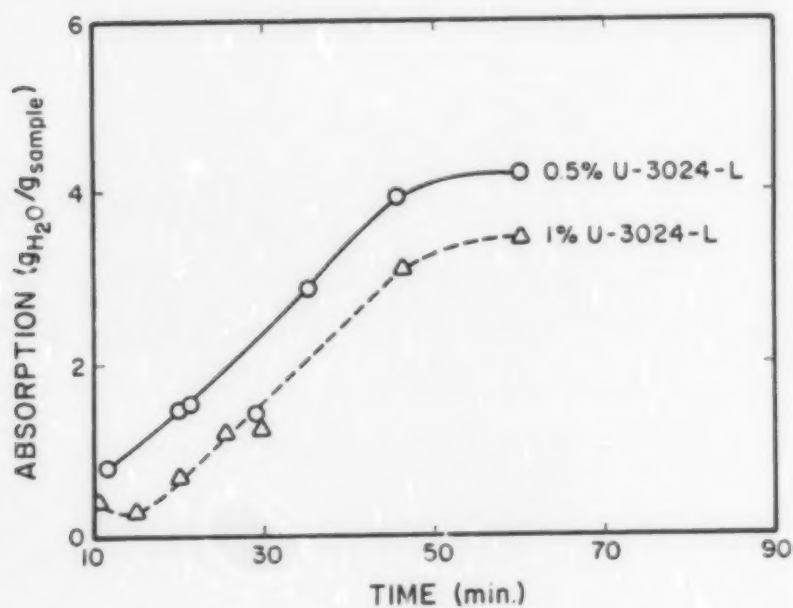


Figure 18d. Water absorption of U-3024-L carbon black foamed glass as a function of time at 850°C.

at all, while about one-half of the F1 carbon was suspended. In comparing the non-wettability of water on the surface of the carbon it was noted that: U-3024-L>F-1>R-1040 and S-315. Similarly, the pore size of the samples follows: U-3024-L>F-1>R-1040 and S-315.

The pellets with low (.5 - 1%) carbon content didn't yield good results at 850-900°C because much of the carbon oxidized before foaming could take place. However, at 2% carbon content the foaming was effective yielding a bulk pellet density of .23 g/cc or of 8.5 lb/ft³. The pellets had relatively non-porous crusts whose water absorption was 10%.

The larger sized foam boards produced had less uniform cell structure than the smaller bulk objects. This is due to the uneven heating rate of the large compacts caused by the insulating qualities of the outer foamed glass. This problem was less acute for decreasing thicknesses of the final foamed product. Products up to 3.81 cm (1 1/2 inches) were easily made with relatively good uniformity.

C. Discussion

From the results of this study it is clearly seen that there are several processes that contribute to the foaming phenomenon.

Immediately upon firing, the carbon begins oxidizing and continues through this process until, at the conclusion of the firing, the density rises and porosity decreases along with a change of color of the inside from black to cream. A reducing atmosphere retards or eliminates completely the crust on the surface. It is apparent, however, that oxidation is not the major source of gas that foams the glass.

Due to the fact that the furnace is preheated, a pellet placed in the furnace will become hotter on the outside faster than the inside; and so foaming will begin on the outside, since it will seal on the outside first and the gases will be trapped. In going to higher and higher temperatures the pore size increases because of two effects. One is the fact that the pores will be sealed by the glass faster since it is less viscous at higher temperatures and the other is that once the envelope has formed, less resistance to the foaming pressures will be exerted because of the less viscous nature of the glass.

A possible reason for the correlation of the non-wetting carbons tested, with the magnitude of pore size and the pH of the material, has to do with the degree of oxidation of the carbon. Since the non-wetting carbons are basic, this indicates that the oxidation hasn't progressed very far and has left many hydrocarbons still present on the surface. If many oxygen groups were present, these carbons would act in a hydrophilic manner. This would leave more hydrocarbons to desorb and give larger pores in the mixture. One of the bases (F-1) is slightly more wettable and its pH is .5 less than the U-3024-L carbon yet the pores in the foam are slightly smaller. This means that it has been more completely oxidized and less hydrocarbons are present for foaming. This is again reinforced because of the extremely large pore size of the coal-glass foam. The coal was composed of hydrocarbon chains with no activation applied. Unfortunately it is hard to obtain coal in the size range needed to obtain small sized foam.

The activated carbons followed a different mechanism since all of the hydrocarbons are carefully removed, leaving an extensive area for the gases to be absorbed. Since there aren't many hydrocarbons present only the absorbed gases foam the glass.

The carbon blacks studied indicate that for a given pH the largest surface area gives the largest pores simply because more gases are allowed to be absorbed on a larger area.

A secondary effect on foaming would be the number of sites available for CO_2 and SO_2 bonding, and the gasification of the carbon itself. These would be the only way that the acidic carbons would be able to foam. This is verified because in a CO atmosphere the pores are reduced in size. According to the reaction $\text{SO}_2 + 2\text{CO} = 2\text{CO}_2 + 1/2\text{S}$, three moles of gas are reduced to two moles of gas. This would reduce the pore pressure and decrease pore size. The carbon monoxide would also inhibit gasification of the carbon according to the mechanism listed in the introduction. To further verify that the SO_2 is present, the manganese removed the H_2S odor as well as decreased the pore size. The manganese was able to reduce the pore size by possibly taking a gaseous component and turning it into a solid phase MnS ; and thereby removing the partial pressure of the SO_2 gas.

The acids have a narrower minimum range in the density than the basic carbons because less gases are produced which can diffuse out and densification can begin much sooner.

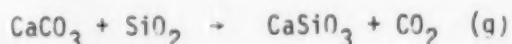
The absorption or open porosity increases linearly since less particles are foaming at the same rate, and as time passes, larger pores form due to the coalescence which, when connected to a channel, increases the length of the open pore.

The more foaming nuclei (carbon particles) there are, the smaller the pores. This is because all the carbon particles give off gases at about the same rate and are thus growing at the same rate. However, when a pore begins impinging on another, its growth stops. The smaller the concentration of foaming nuclei, the larger the pores will become before impingement occurs. For the same reason the higher concentrations of carbon in the carbon-glass mixture reach minimum density faster because all the available area is foamed faster because of the more numerous nuclei.

Finally, because the rate of pore size increase is smaller for the higher percent carbon; it is thought that the glass through which the pore is expanding is slightly more viscous due to the higher carbon content.

VI. CALCIUM CARBONATE AS THE FOAMING AGENT

CaCO_3 can also be used as a foaming agent. In this case the glass is ground to an average particle size of one to twenty microns. The glass does not require color sorting, sizing, or cleaning. Calcium carbonate (CaCO_3) and bentonite are next mixed with the ground glass. The bentonite is added to improve the plasticity of the mixture so that it can be easily extruded or pressed into blocks. As the dried mixture is placed into a furnace at approximately 800°C , the CaCO_3 reacts with the glass (largely SiO_2) as follows:



The CaO being thus incorporated acts as a glass modifier reducing the viscosity of the glass. At this same temperature, the glass particles begin to sinter. The sintering prevents the carbon dioxide gas from escaping by sealing off the passage ways. The pressure of the gas can then expand the molten glass into a low-density cellular structure. This process is used to produce both large blocks or slabs and pellets of foamed glass.

Foam glass in the form of pellets possibly can provide wider applications for foam glass as a structural insulating material. Combining with proper binders, the pellets can be manufactured in any size or shape without waste. Another advantage is that glass can be foamed more uniformly due to faster heat transfer throughout the pellets. One drawback is the formation of a thick skin on the surface of the CaCO_3 foamed pellets which increases the overall density and reduces the insulating characteristics of the pellets.

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Exposure to moisture over a significant length of time may cause the glass insulation to deteriorate, resulting in a loss of insulating quality and structural strength. In order to lower the solubility, bentonite clay is mixed with the glass prior to foaming. The relatively high content of Al_2O_3 in the clay decreases the solubility of the glass. The function of the clay is then two fold - to lower the solubility and to act as a plasticizing agent for extrusion.

A. Experimental Procedure

Clear soda-lime cullet is used throughout the experiments. Grinding was done in a two foot diameter ball mill with steel balls. Each batch containing thirty to forty pounds of glass was ground for two hours. The final size ranged from one to twenty microns. The CaCO_3 and bentonite was mixed with the glass in smaller rubber lined ball mills 20 cm (8 inch diameter) using alumina balls.

The standard size disk-shaped samples for foaming tests each weighed 65 grams and are 6.5 cm in diameter. The samples were placed directly into a preheated electric furnace for a set length of time,

and then they were withdrawn directly to room temperature. In addition to these standard samples, larger samples 23 cm (9 inches) by 13 cm (5 inches) by 3.8 cm (1 1/2 inches) were prepared to assure that the relationships between the various parameters are consistent for different sizes.

When working to form foam glass pellets the waste plate glass was crushed and ground in a ceramic ball mill for one day and the particle size distribution was determined by Coulter Counter as:

< 3μ ; 25%

3 ~ 10μ ; 50%

15 > 10μ ; 25%

The surface area of this glass powder also obtained by BET test is $3.34\text{m}^2/\text{g}$. The powder was mixed with 2% CaCO_3 and 4% high-swelling bentonite and extruded into cylinder shape with 3 different diameters. The extruded samples were dried and cut into small pellets of differing lengths. The pellets were foamed at various temperatures and time and foaming characteristics were observed. The procedure for the solubility test was as follows:

1. Crush the foamed glass and sieve to a -40 to +50 mesh size.
2. Wash with alcohol to remove fines from the surface of the particles.
3. Dry in drying oven at 120°C for 12 hours.
4. Weigh a sample approximately 7-1/2 grams to 10 grams.
5. Add 250 ml distilled water to sample (in 250 ml plastic beaker with lid).

6. Place beaker in 90°C water bath for six hours.
7. Filter and dry in oven at 120°C for 12 hours.
8. Weigh residue and determine loss.

In order to see the effect of glass particle size on the density of the foamed glass, four samples composed of different particle sizes were prepared. ⁽¹⁾ Each sample was mixed with 1% CaCO_3 and pressed into the form of a disc at 500 psi. After foaming for 5 minutes at 800°C, the change in pore size and bulk density of the products was observed.

Thermal conductivity measurements were done using the rapid K-factor method and standardized to Pittsburgh Corning foam with .4 BTU/hr. °F ft.²/in. The K-factor of CaCO_3 foam vs density and cell size was determined.

B. Results and Discussion

During earlier investigation, glass containing 1.0 to 2.0 percent CaCO_3 was foamed at temperatures ranging from 700°C to 800°C, often resulting in an open-cell foam structure. A closed-cell structure, which improves the insulative qualities of the foam, was obtained by foaming at temperatures near 800°C using approximately 0.5 to 1.0 percent CaCO_3 . However as noted on Table 9, as time in foaming increases the open porosity also increases. The cell size as a function of the percent CaCO_3 and the foaming time are shown in Figures 19 and 20 respectively.

As shown in Figure 19 the type of CaCO_3 affects the foaming characteristics. Milled limestone and reagent grade CaCO_3 have similar size distribution and structure. However, the foaming qualities are significantly different between the two. A high-purity

Table 9.
OPENING OF PORES WITH INCREASING FOAMING TIME

<u>Sample</u>	<u>Foaming Time</u>	<u>Water Absorbed (wt.%)</u>
Foamed at 850°C 1%CaCO	3 minutes	25.0%
	5 minutes	84.5
	8 minutes	138.5

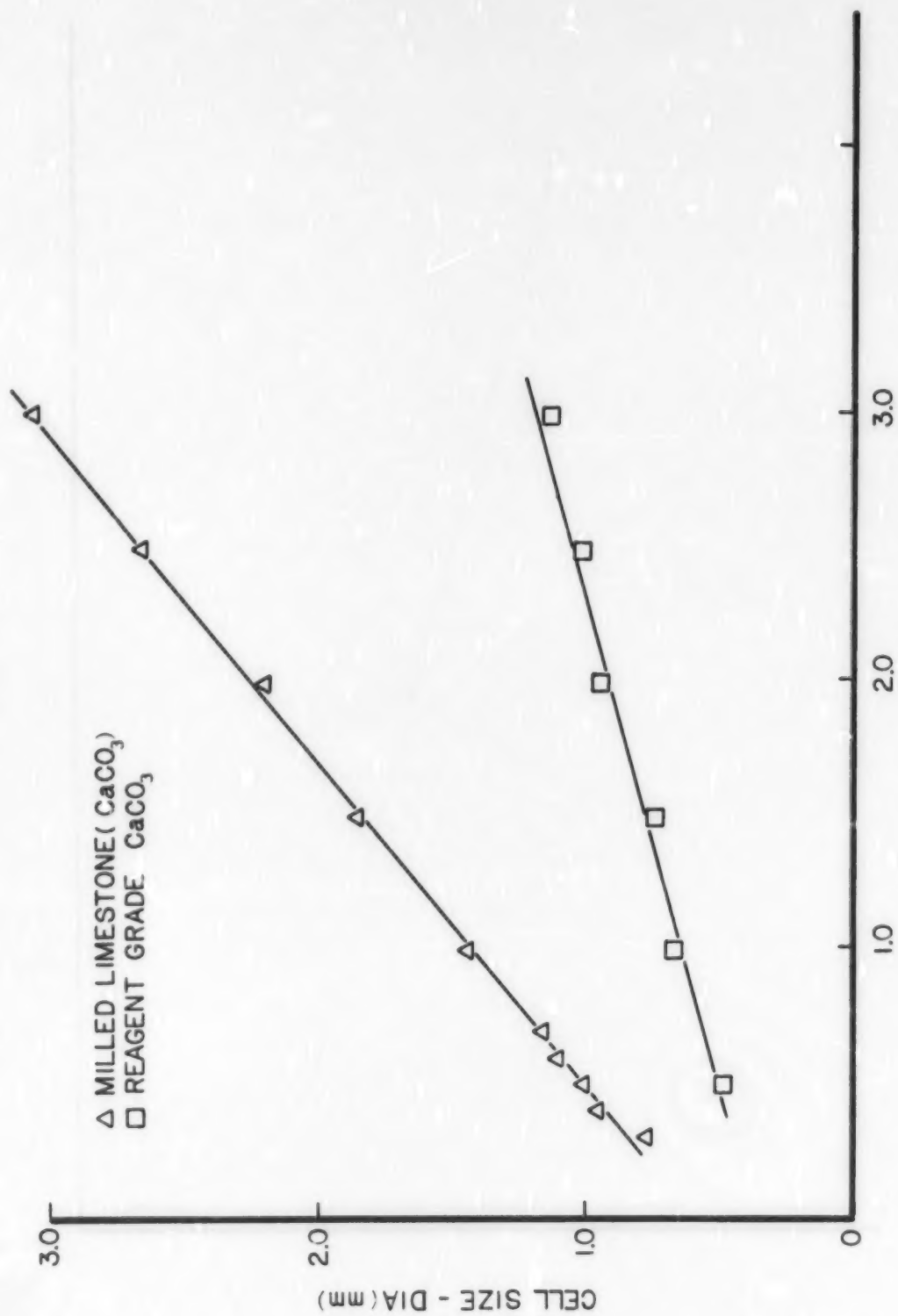


Figure 19. Cell size versus percent calcium carbonate.

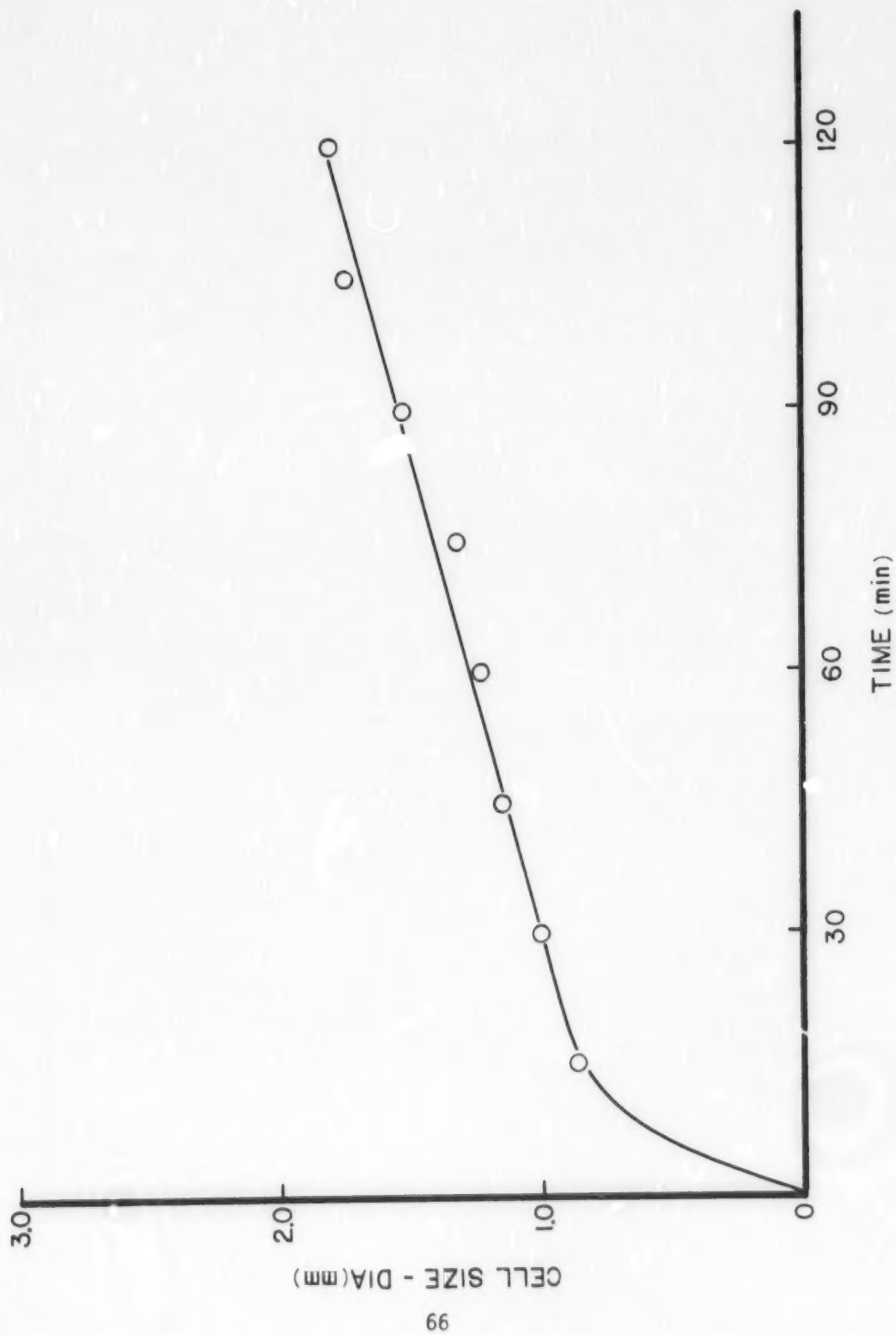


Figure 20. Cell size versus foaming time.

precipitated CaCO_3 was tested and found to be inferior to the milled limestone. Since the reactivity of the CaCO_3 is inversely related to the surface area, the precipitated CaCO_3 probably reacts before the surrounding glass particles can sinter to seal off the passageways. Figure 21 compares the firing temperature time and percent CaCO_3 added. Uniform cell size was only possible when the entire furnace was within 25°C of the operating temperature and fired according to the other variables shown. The milled limestone and reagent grade CaCO_3 produce higher quality foam as the particle size of the CaCO_3 decreases as shown in Figure 22. The best foaming occurred when the CaCO_3 particles were from 10 to 50 μ .

Because of the ease in producing large amounts of milled glass, large 7.6 cm (3 inches) by 30 cm (12 inches) by 60 cm (24 inches) pieces of CaCO_3 foam were produced. When working with large pieces care had to be taken in heating during foaming. Figure 23 gives examples of the heating curves used. Only the one curve would produce uniform small (~ 2 mm) pores. Total heating time was typically four hours for the largest pieces.

Table 10 shows the properties of the various pellets which were foamed at the same conditions. The density of bulk foam block was also listed for comparison. Much higher densities of foamed glasses were obtained for foamed pellets. It should also be noted that the densities of foamed pellets increase with decreasing sizes of the original extruded pellets. These results can be explained by the so called "skin effect". When a pellet is heated, the surface

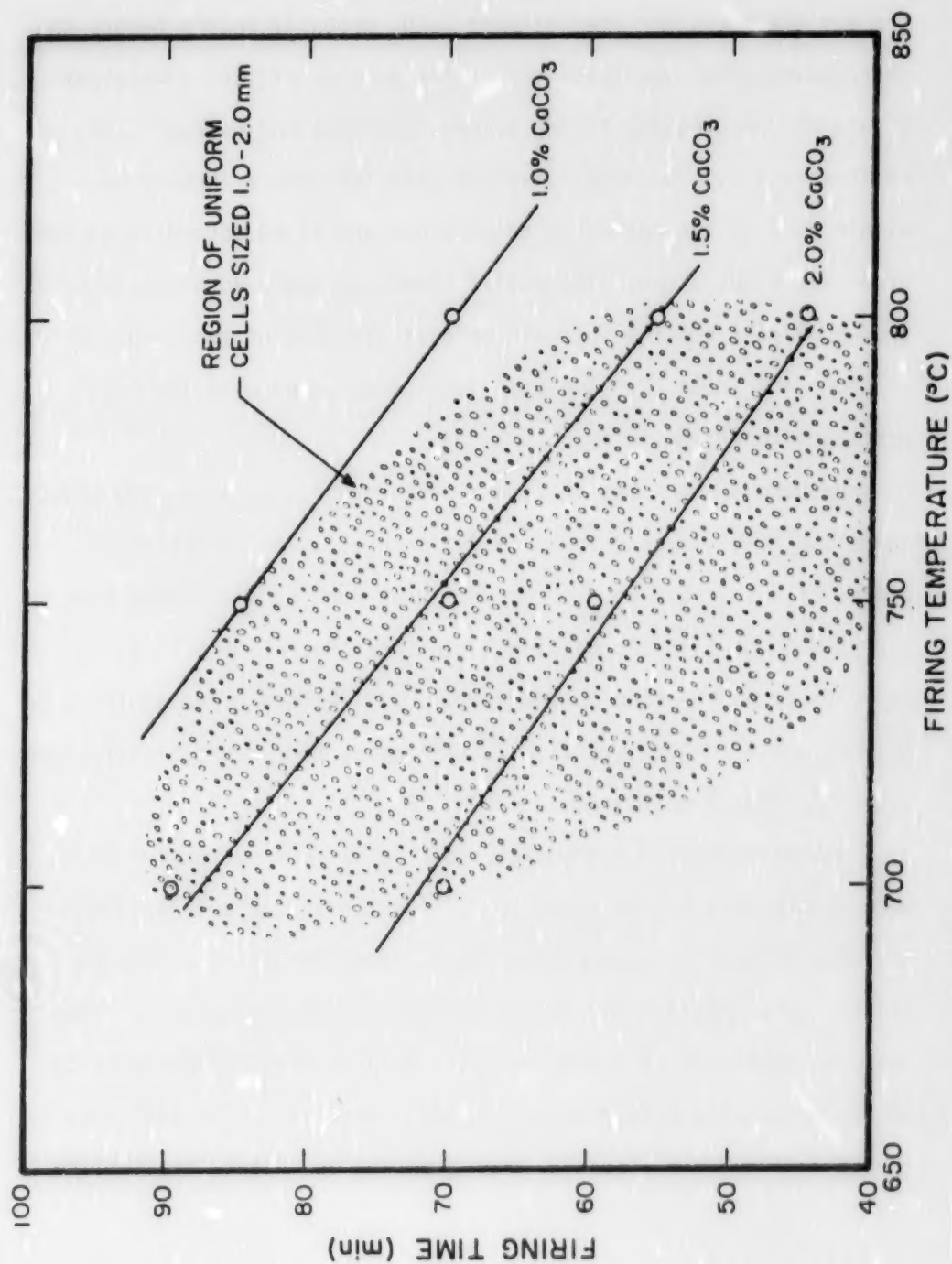


Figure 21. Firing time versus % CaCO_3 vs. temperature. Samples expanded 6 times its volume.

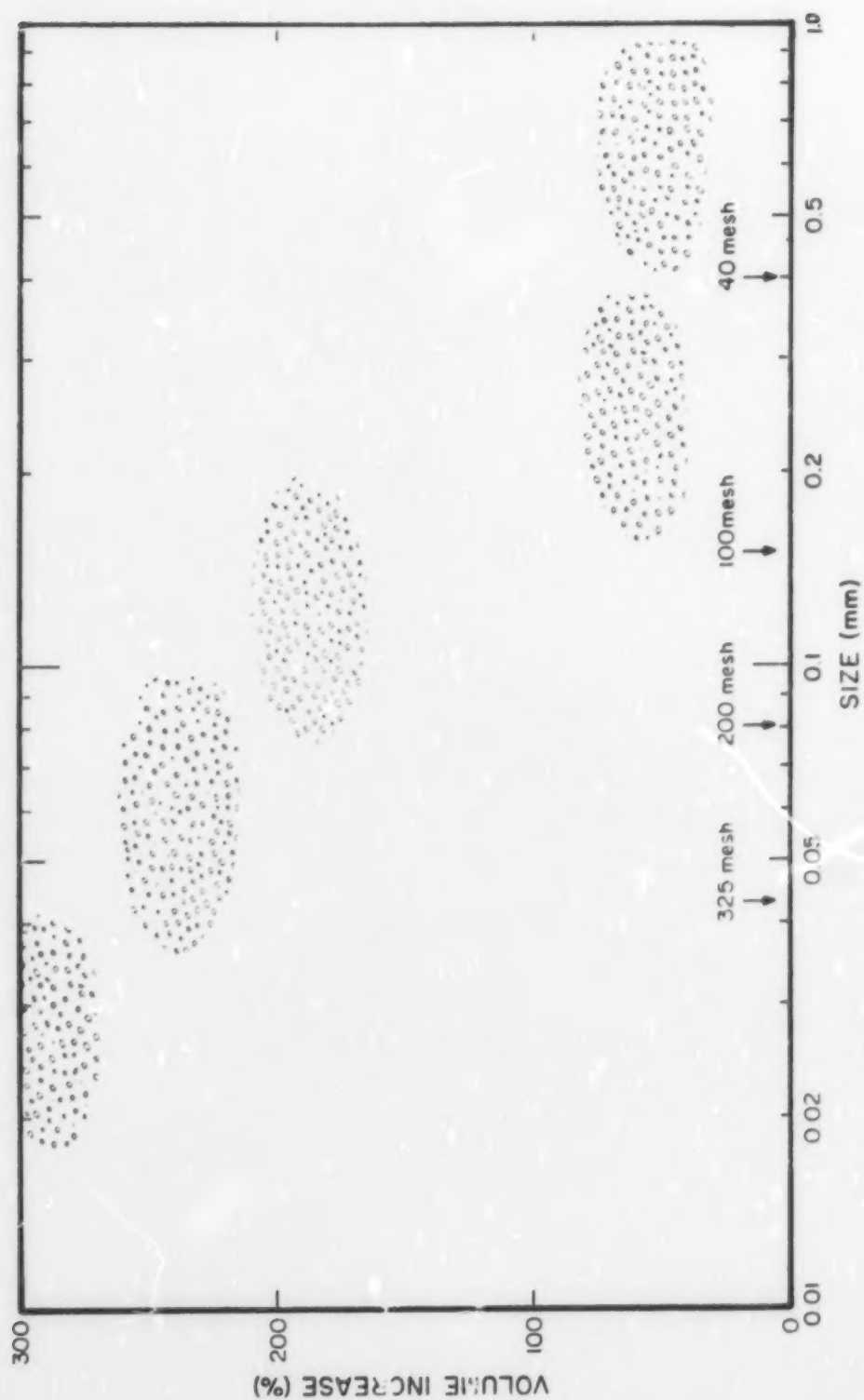


Figure 22. Volume increase vs. CaCO_3 size for 10-20 μ cullet at 700°C for one hour and 0.5% CaCO_3 .

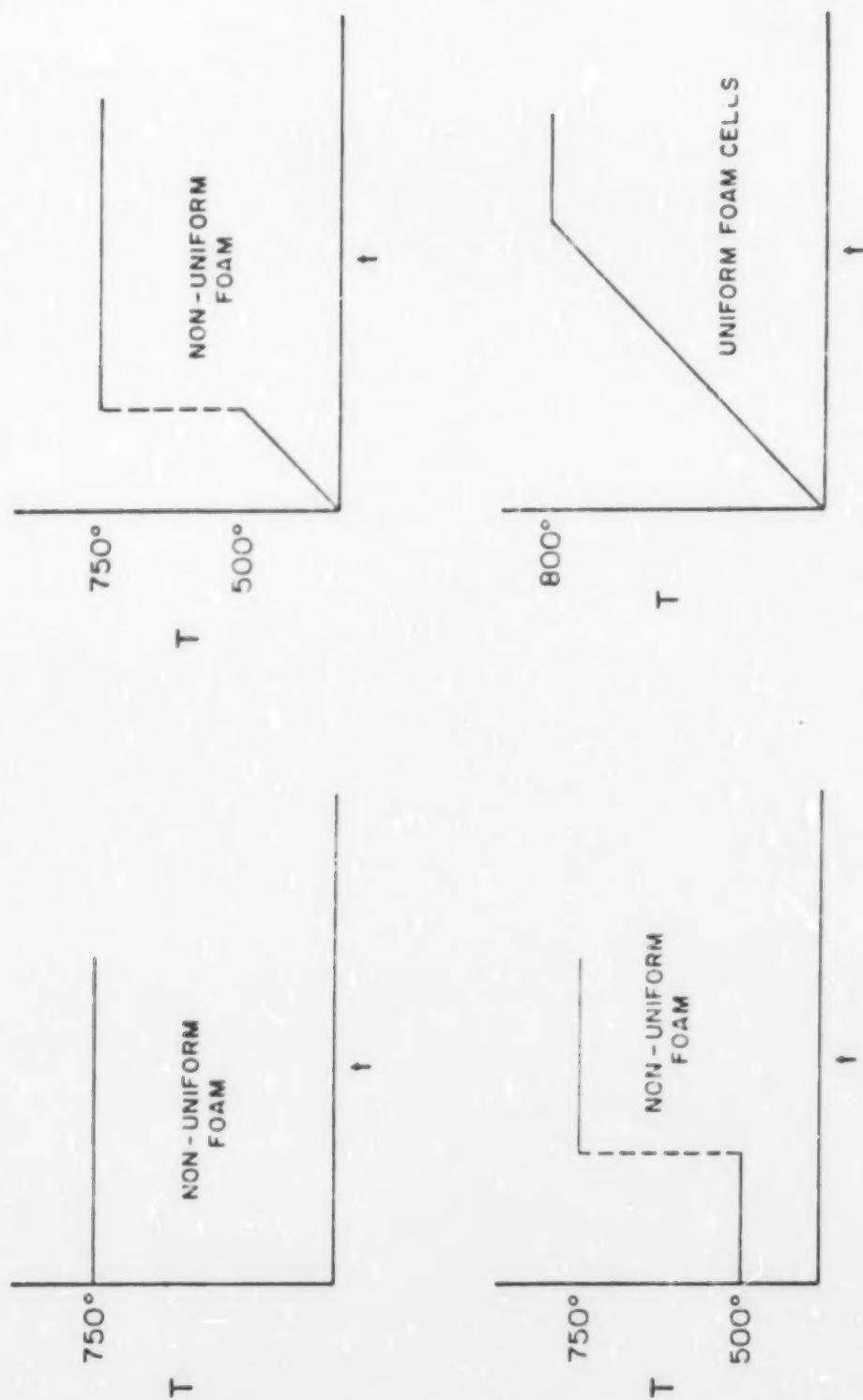


Figure 23. Large scale sample foaming schedules (CaCO_3 type).

Table 10.

PROPERTIES OF FOAMED GLASS PELLETS
(FOAMED AT 850°C FOR 5 MINUTES WITH 2% CaCO_3)

Sample	Size of Sample before foaming		Bulk Density after foaming (g/cm^3)
	Diameter	Height	
Pellet #1	1.27cm 1/2"	1.27cm 1/2"	0.312
#2	.48cm 3/16"	.48cm 0.370	
#3	.19cm 3/40"	.19cm 3/40"	0.410
Block foam Glass			0.230

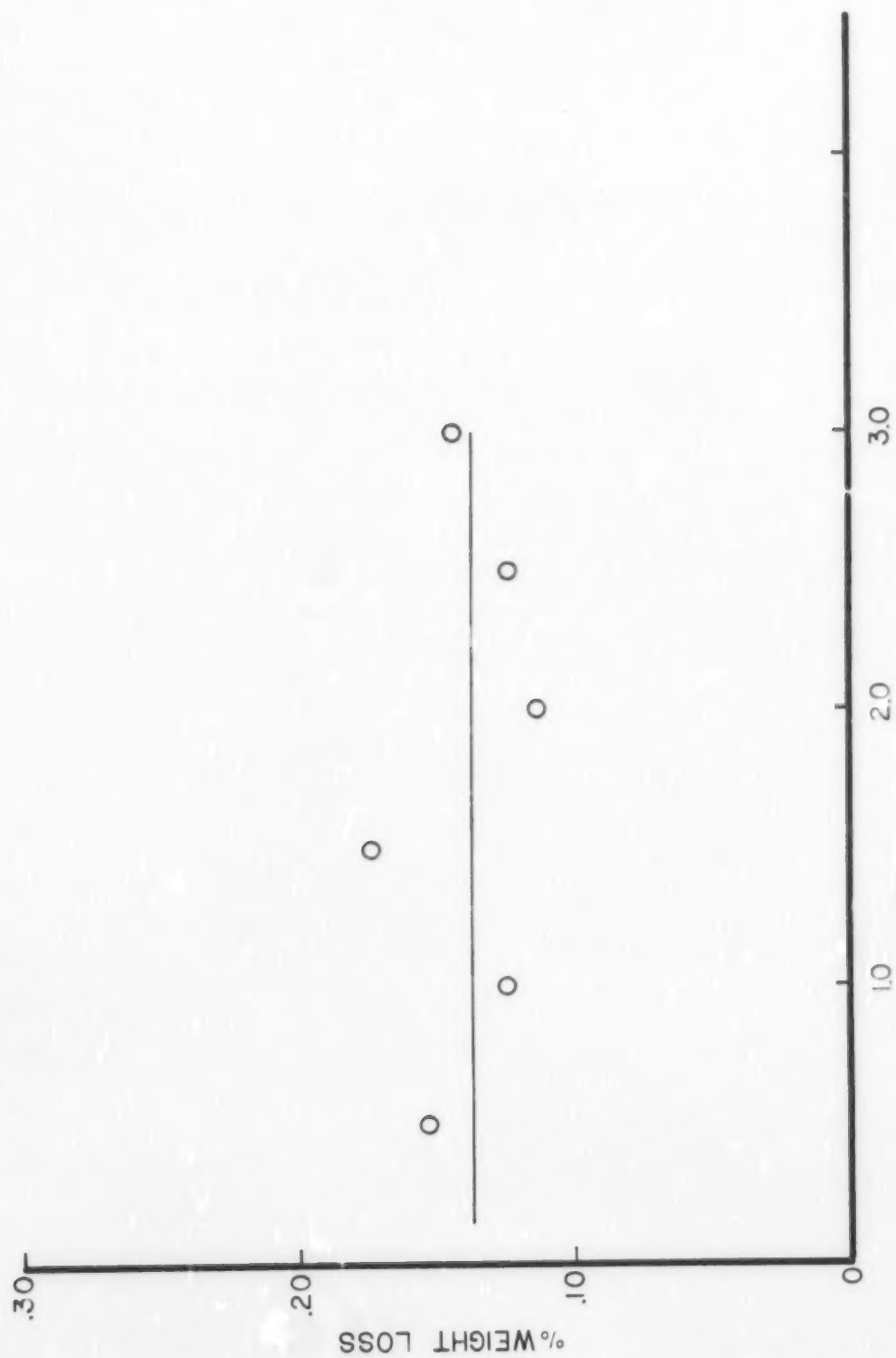
looses most of the CO_2 before the glass seals off its passage. Eventually this portion sinters without any foaming and results in a high density product.

The solubility of foamed glass in water decreases as the percent of clay increases. The solubility, however, is not affected by the CaCO_3 content (Figure 24). The typical chemical analysis of the clays used are shown in Table 11.

The higher the alumina content of the glass due to the addition of the clays, the lower the solubility of the glass. Figure 25 shows the solubility as a function of clay additives. The minimum amount of bentonite needed to extrude the glass mixture is two percent. At this percentage, the solubility has decreased by 24%.

Clay content greater than approximately 6% lowers the quality of the foam by increasing density and decreasing cell uniformity. The sample with low-swelling bentonite, foamed at a lower temperature (780°C) does not show any effect of clay addition while the same sample, foamed at a higher temperature, does.

This result may indicate that there is a minimum temperature for each clay to be dissolved in the glass structure and affect the solubility of glass. As can be seen from Table 12 the best foam for uniformity was for glass with a particle size below 10 μ . The density attained here was $\sim .4 \text{ g/cm}^3$. As seen from Figures 26 and 27 the K factor is a function of density and cell size whose minimum value is about $.4 \text{ BTU/hr } ^\circ\text{F ft}^2/\text{in.}$



73

% CALCIUM CARBONATE

Figure 24. Percent weight loss (solubility) versus percent CaCO_3 .

Table 11.
CLAY ADDITIVES

Clay	Source	Main Composition (wt.%)			
		SiO ₂	Al ₂ O ₃	Na ₂ O+K ₂ O	CaO
Ball Clay (Old mine #4)	Kentucky-Tennessee Clay Company	52.0	31.2	1.3	0.4
Low-Swelling bentonite	American Colloid Company	57.0	20.0	1.0	2.0
Plantsite (Harrisville Brick Plant)	local	55.0	12.0	3.0	10.0
High Swelling bentonite		64.0	21.0	3.0	0.5

Table 12.
EFFECT OF PARTICLE SIZE OF GLASS ON FOAMING

Sample No.	Particle Size (μ)	Pore Size (mm)	Properties of Foam		Uniformity
			Bulk Density (g/cm ³)		
1	>10	~2	~0.40		Best
2	10~43	~1	~0.45		Good
3	43~61	~1	~0.55		Bad
4	61~74	~1	~0.80		Bad

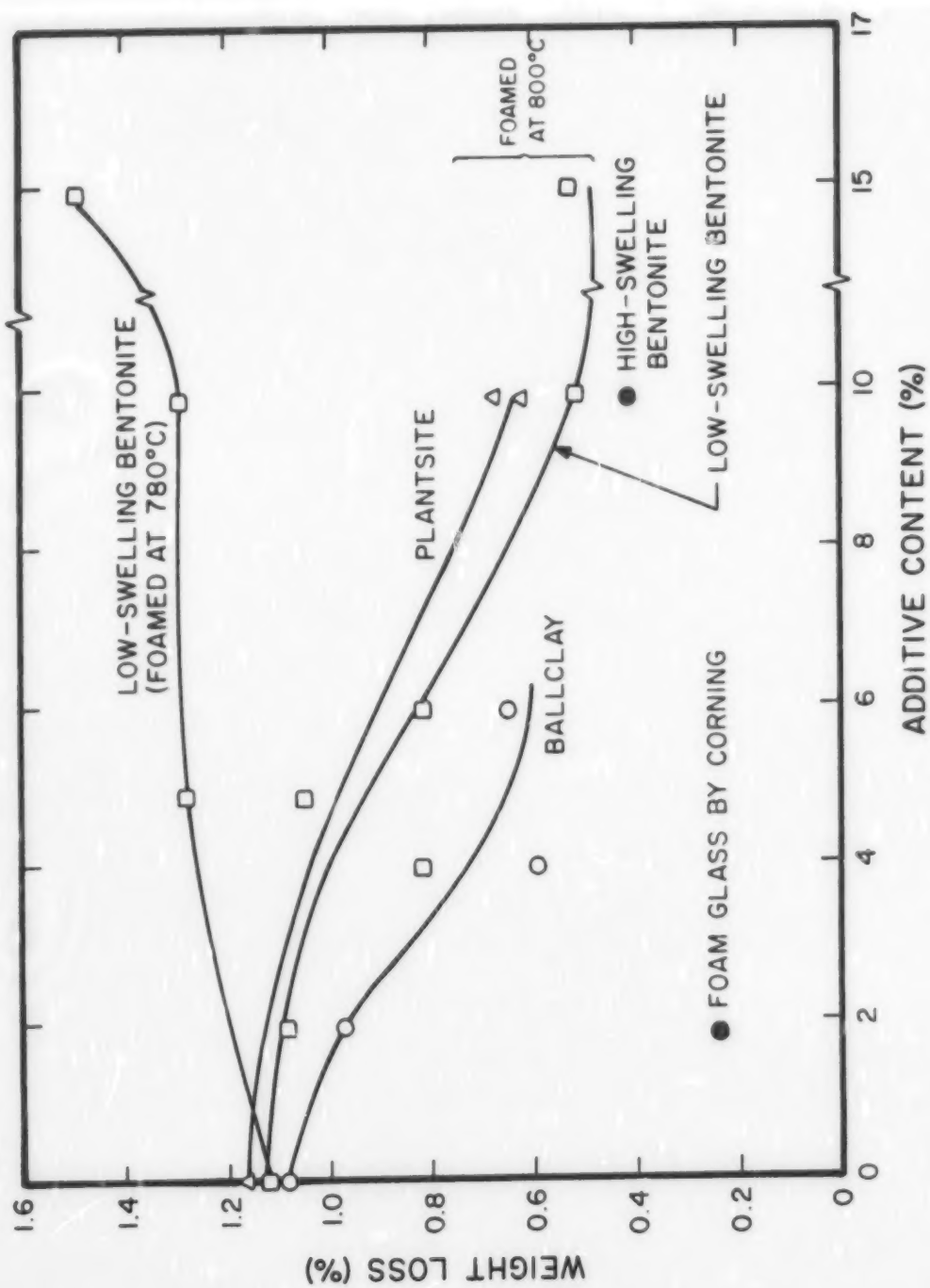


Figure 25. Solubility change of foam glass in water with clay additives.

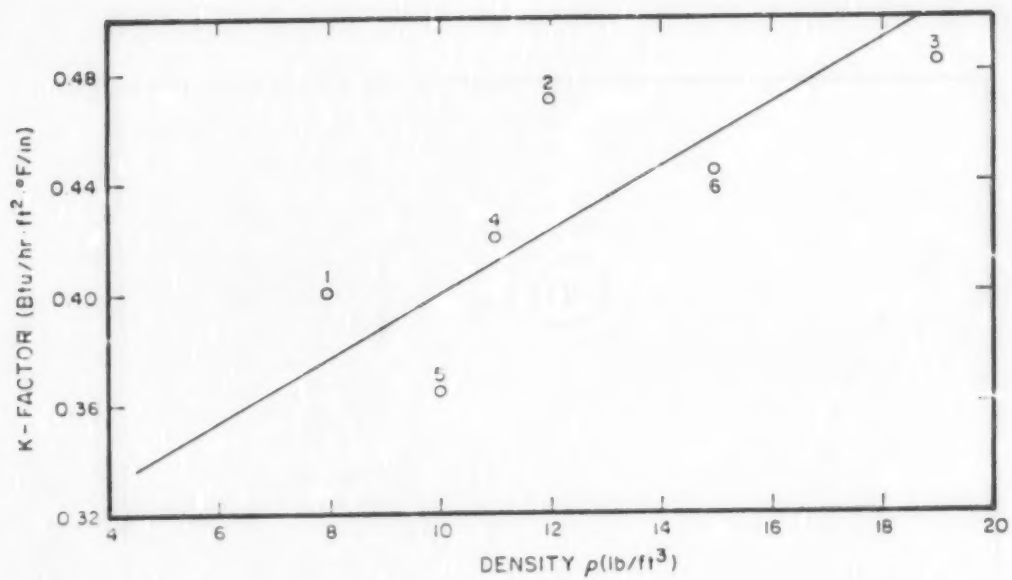


Figure 26. K-factor of CaCO_3 foam vs. density.

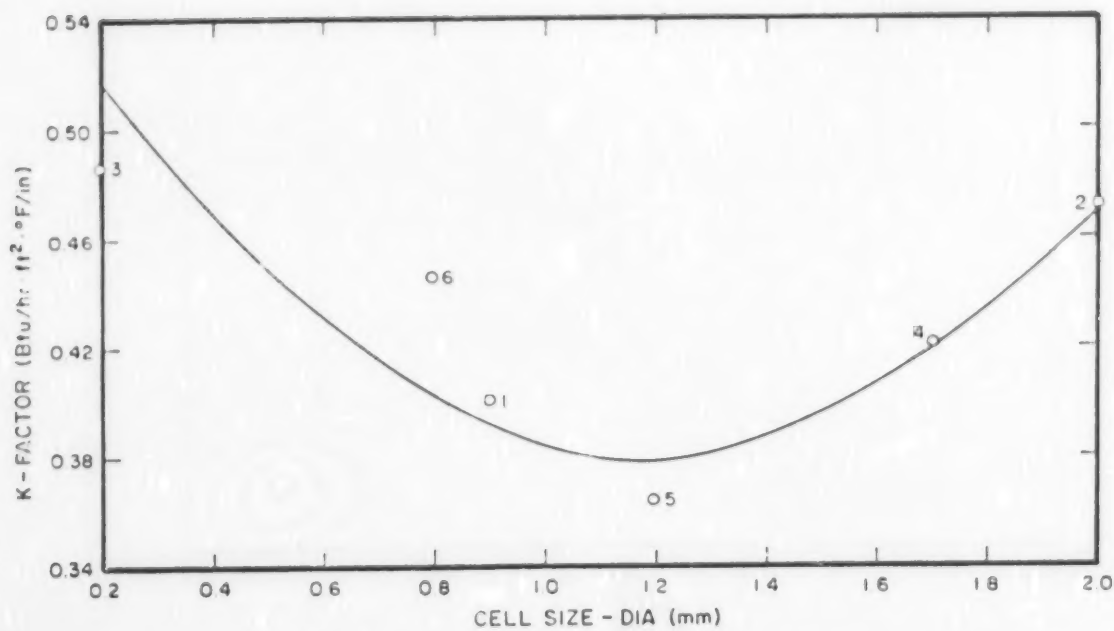


Figure 27. K-factor CaCO_3 foam vs. cell size.

The properties of the CaCO_3 glass compared well with commercially produced foam glass. Density varied around 10 pounds per cubic foot. Compressive strength averaged over 8 kg/cm^2 (125 pounds per square inch) and is sensitive to annealing. The high insulating quality, as indicated by the K-factor, varied with density and cell size. The foamed glass will not burn but does have a tendency to abrade under a flame.

VII. SUMMARY OF FOAMING METHODS

Each foaming agent has some characteristics that distinguishes it from another that would make it useful in a particular application. Water impregnated glass can foam particles as small as 177 microns. This will be an asset as a filler material as well as an insulation since good foaming can easily be done in pellets up to .62 cm in diameter. In proceeding to larger dimensions considerable control of temperature and water content is necessary to obtain uniform pores.

Carbon black foaming is limited from a small pellet size of .32 cm to large slabs. The foaming produces uniform pores and is reproducible if the furnace temperature is uniform. The crust or shell is not very thick and can essentially be eliminated if foamed in a reducing atmosphere.

Calcium carbonate produces pores that are more than twice the size of the carbon foamed pieces and has a thicker crust associated with it. The bulk density was also a little higher than the carbon foamed glass.

From these observations it appears that water is best suited for foaming glass from a 177 micron size to pellets .32 cm in diameter. Carbon black gives the best results for objects between .64 cm and 5 cm.

VIII. MARKET POTENTIAL OF FOAMED WASTE GLASS Insulation and Concrete Aggregate Markets

The development of foamed waste glass stems from a current trend in the United States to conserve natural resources and to decrease pollution. Solid waste refuse is one form of that pollution. Recycling and re-use of the refuse conserves that portion of the original raw material which is replaced in a new product by the recycled material. If components of refuse can some day be economically separated, recycled, and marketed by industry, the pollution from solid waste will be reduced significantly. Research concerning the recycling of solid waste has provided economical ways to recover various components of the solid waste refuse. The implementation of solid waste separation and use of the output on a widespread commercial basis remains to be done.

Solid waste is composed of metallic, organic and ceramic material. The metallic and organic fractions are either already valuable and recoverable or can be incinerated to recover the fraction as thermal energy. The ceramics fraction, however, is by comparison of low value. This is because the raw materials are generally non-critical and widely available. Glass is part of the ceramic fraction and constitutes about 6½ percent of all solid waste. The glass fraction of solid waste can be separated.

There are more potential uses for salvaged waste glass than there is glass available now or in the foreseeable future. If the salvaged waste glass from Los Angeles, St. Louis, New York, Washington, D.C., Detroit, San Francisco, Denver and Chicago was crushed and used for

asphalt aggregate in those cities, only 50 percent of the aggregate needed could be provided. Color separation is required for some uses such as recycling into bottles. Another way to recycle waste glass is to foam it and use the foamed waste glass rather than the broken glass. More research has been done on the use of crushed waste glass than on foamed waste glass--probably because crushed glass was more readily available. Foamed waste glass requires another process (foaming) to produce a usable raw material. However, in many instances such as concrete aggregate, the properties of foamed glass seem to provide a broader base for use than the crushed glass.

Uses for foamed glass have been suggested in previous literature, but little has been published to evaluate the market potential of foamed waste glass.

The objective of this study is to determine the market demand for foamed waste glass. Market demand is analyzed with respect to the two principal uses of foamed waste glass: (1) rigid insulation and (2) lightweight concrete aggregate. In each case the market demand is determined on a national and regional basis. The discussion of market demand is followed by an analysis of the production cost of foamed waste glass. Production cost information is relevant because these costs determine the market price of the product and are therefore very important indicators of market potential. The market price of foamed waste glass is particularly significant because of the price differential between foamed waste glass and existing rigid insulation products.

Other desirable features of foamed glass insulation include its strength and rigidity. Flexible, blanket, and batt insulations cannot support any significant weight. Because of the strength and rigidity of foamed glass, it will not slump or compress. This eliminates voids and sagging.⁽²⁶⁾ The high compressive strength and low density also make it an ideal construction material. Foamed glass will support an average, ultimate load of seven tons per square foot with a compressive strength greater than 100 psi. Therefore, less material needs to be used to create supporting structures. Other than the minimal steel support structure, four-inch thick foamed glass has been used as the exterior wall of a building. Tapered blocks may be used to create a roof deck, and thin slabs of foamed glass have been used as insulation in parking decks and over concrete sub-floors.⁽²⁵⁾ The rigidity of the cellular foam in combination with the vapor barrier created by cellular glass is excellent for many tasks in which no other insulation can meet the specifications.

Because of the incombustible material from which foamed glass is made, no fireproofing is necessary. This is especially important in public buildings where fire hazards are of prime concern.

Other types of rigid insulation are not competitive with foamed glass in uses where the object to be insulated requires a vapor barrier.

A. The Market Potential for Rigid Insulation

Rigid insulation is an important construction material used in non-residential construction. A small segment of this rigid insulation market has been captured by FOAMGLAS, a Pittsburgh Corning Product,

which is relatively expensive and is used only in high quality non-residential construction. Foamed waste glass, as produced by the (Table 13) University of Utah, possesses many of the highly desirable properties of FOAMGLAS, i.e., waterproof, incombustible, rigid, and dimensionally stable. Although there are many physical similarities between FOAMGLAS and foamed waste glass there is a significant price difference between the two products. Pittsburgh Corning FOAMGLAS is priced at 24-26¢ a board foot compared to only 8-10¢ a board foot for foamed waste glass. If foamed waste glass proves to be a close substitute for FOAMGLAS this wide price differential will make foamed waste glass very competitive with Pittsburgh Corning FOAMGLAS and provide easy entry into the rigid insulation market. However, it should be emphasized that the national market for FOAMGLAS as rigid insulation is very small.

In 1974 the FOAMGLAS market was approximately 100 million board feet valued at about \$25 million.⁽¹⁹⁾ At this production level, one 40/ton/day plant would need to capture (in terms of total board feet) over 25 percent of the existing market and 7 percent of total value of the national market. Nevertheless, the wide price differential between foamed waste glass and FOAMGLAS would very likely lead to a substantial expansion of the existing market and reduce that percentage of the market that would need to be captured by a new foamed waste glass plant.

It is estimated that foamed waste glass as rigid insulation could be produced and sold for 8-10¢ a board foot. If this selling price were achieved, foamed glass would be very competitive with all other roof insulation products. Fiberboard, fiberglass board and Fesco board, the principal roof insulation products, all sell for more than 10¢ a board

Table 13
COMPARATIVE VALUES OF SELECTED PHYSICAL PROPERTIES
OF INSULATION: RIGID

Property	University of Utah Foamed Glass	Pittsburgh-Corning (P.C.) Foamed Glass	Other
Size (dimension in inches)	Assumed similar to Pittsburgh-Corning (P.C.) Assumed similar to P.C.	24 x 18 x 4 ⁽²⁶⁾ Other sizes are available or cut or molded lesser sizes or shapes desired ^a	
Density (lb./ft. ³)	10 - 15 ⁽¹⁹⁾	9 ⁽²⁴⁾	Perlite 3 - 4 ⁽¹⁶⁾
Compressive Strength (psi)	> 100 ⁽¹⁹⁾	100 ⁽²⁴⁾	
Thermal Conductivity	.4 ⁽¹⁹⁾	.4 ⁽²⁵⁾	Perlite .3 - .5 ⁽¹⁸⁾
Combustibility	Will not burn ⁽²⁵⁾	Will not burn ⁽¹⁸⁾	Perlite - Will not burn ⁽¹⁸⁾

*Note: Numbered footnotes in parentheses refer to references at end of text material.

^aSuch as tapered thickness for roofing and curved for pipes.

foot and none of them have the wide range of qualities possessed by foamed waste glass. The high quality and low price of foamed waste glass would increase the size of the market from \$25 million to \$100 million (value of entire non-residential roof insulation market). Nevertheless, limited application for the residential construction market would continue.

Given the price differential and inherent quality advantages of foamed waste glass, it is assumed that foamed waste glass would capture 20 percent of the roof insulation market. Tables 15 and 16 supply important information about the size and value of the rigid insulation market and the number of 20/ton/day plants required to meet projected production levels.

The data shows that the foamed waste glass market for rigid insulation in the Western United States has been sufficient to support two 20/ton/day plants and the national market has been sufficient to support fourteen 20/ton/day plants.

B. Characteristics of Foamed Waste Glass as Lightweight Concrete Aggregate

The term "lightweight aggregate" describes a range of concrete aggregates that have a weight considerably below that occurring in sand and gravel. Lightweight aggregates range from the extremely light materials used for insulative and non-structural concrete all the way to expanded clays and shales used for structural concrete. In general, the low density lightweight aggregate concretes at the left end of the concrete spectrum (Figure 28) are used primarily for insulating purposes, as they have relatively low compressive strength; while those in the middle range are used for insulation and fill. The lightweight concretes at the upper end of the spectrum develop excellent compressive strength and are found in a number of structural applications.

Table 14
Western Market for Non-Residential Rigid Roof Insulation
(millions of dollars and board feet)

Year	Total Value Non-Resid. Construction	Total Value of Non-Resid. Roof Systems	Mkt. Value of Rigid Roof Insulation	Value of 20% of the Rigid Roof Insul. Mkt.	No. of Bd. Ft. of 20% of the Roof Insul. Mkt.	No. of 20 Ton/Day Plants Rqd
1971	\$4,051.5	\$125.6	\$12.6	\$2.5	31.8	2.27
1972	4,770.7	147.9	14.3	3.0	35.9	2.56
1973	5,980.9	185.4	18.5	3.7	41.7	2.98
1974	6,271.9	194.4	19.4	3.9	41.4	2.96
1975	5,822.9 ^a	180.5 ^b	18.1 ^c	3.6	36.0 ^d	2.57 ^e

Table 15
National Market for Non-Residential Rigid Roof Insulation
(millions of dollars and board feet)

Year	Total Value Non-Resid. Construction	Total Value of Non-Resid. Roof Systems	Mkt. Value of Rigid Roof Insulation	Value of 20% of the Rigid Roof Insul. Mkt.	No. of Bd. Ft. of 20% of the Roof Insul. Mkt.	No. of 20 Ton/Day Plants Rqd
1971	\$25,590.2	\$793.3	\$74.3	\$15.9	202.3	14.45
1972	27,118.9	840.7	84.1	16.8	201.2	14.37
1973	31,761.4	984.6	98.5	19.7	222.1	15.86
1974	33,859.5	1,049.6	105.0	21.0	222.9	15.92
1975	30,336.3 ^a	940.4 ^b	94.0 ^c	18.8	188.0 ^d	13.43 ^e

(Source and Footnotes apply to both Table 14 and Table 15).

Source: Compiled by Bureau of Economic and Business Research, University of Utah, Salt Lake City, Utah, 1976.

^aMcGraw-Hill, *Building Cost Calculator and Valuation Guide* (New York, New York: McGraw-Hill Information Systems Company) 1976.

^bMcGraw-Hill, *1976 Dodge Construction System Costs* (New York, New York: McGraw-Hill Information Systems Company) 1975. From this source it was determined that 3.1% of the cost of non-residential construction was the cost of the roof system.

^cSame footnote as b. 10% of the cost of a roof system is the cost of insulation.

^dDetermined by dividing the value of market by average board foot cost of roof insulation.

^eDetermined by dividing the total annual production of a 20 ton/day foamed waste glass plant into millions of board feet of 20% of the roof insulation market.

Table 16
COMPARATIVE VALUES OF SELECTED PHYSICAL PROPERTIES OF
CONCRETE AGGREGATE

Property	University of Utah Foamed Glass	Pittsburgh-Corning (P.C.) Foamed Glass	Other
<u>Lightweight Aggregate</u>			
Size (diameter in inches)	Assumed similar to Pittsburgh-Corning (P.C.)	.2 - .25 (15)*	
	Assumed similar to P.C.	.25 - .625(27)	
	Assumed similar to P.C.	.94 - 1.89(15)	
Density (bulk, lb./ft. ³)	14 - 20 Assumed similar to P.C.	6 - 8 (15)	Perlite 7 1/2 - 20 (17, 31, 21)
Compressive Strength (psi)	>100 (19)	100 (27) ^a	Perlite .27 - .40 (16)

*Note: Numbered footnotes in parentheses refer to references at end of text material.

^aWill not settle.

Table 16 (Continued)

Property	Pittsburgh-Corning (P.C.)		
	University of Utah Foamed Glass	Foamed Glass	Other
<u>Lightweight Aggregate</u>			
Temperature Range	Up to 800°F (18)	-3000 to 1,000°F (15)	Up to 1,500°F (16)
<u>Lightweight Concrete Properties</u>			
Weight ⁹ (lb./ft.)	Assumed similar to P.C.	30 - 40 (15)	42 - 60 (15) Perlite 20 - 80 (16) Vermiculite 35 - 75 (17) Clay and Shale 90 - 110 (17)
Cure Time	Assumed similar to P.C.	Short (15)	
Compressive Strength (psi)	Assumed similar to P.C.	Achieved quickly (15)	Vermiculite 50 - 600 (17) Perlite 95 - 400 (21) Gilsomite 1,047 (17) (16) ^e Perlite 1,000 - 2,000

^e A special Perlite for stucco and precast masonry.

Table 16 (Continued)

Property	University of Utah Foamed Glass	Pittsburgh-Corning (P.C.) Foamed Glass	Other
<u>Lightweight Concrete Properties</u>			
Dry Shrink (percent)			Gilsonite .034 ⁽²¹⁾
Thermal Conductivity			Perlite .5 - .8 ^{(21)b} Clay and Shale 1.7 - 5.2 ^{(21)b}
Other		Water requirement (15) drastically reduced	

^b Any lightweight has an insulation value approximately four times greater than ordinary concrete.

Table 16 (Continued)

Property	Lightweight Aggregate		
	University of Utah Foamed Glass	Pittsburgh-Corning (P.C.) Foamed Glass	Other
Thermal Conductivity BTU/wq. ft., hr. in., degrees F.	.4(9)	.42 - .45(15)	Diatomite .6 - .7(18) ^b Perlite .3 - .5(18) ^b Vermiculite .4 - .7(18) ^b
Alkali/Acid Resistance	Assumed similar to P.C.	Resistance includes hydrofluoric and phosphoric (15)	
Solubility in Water	24% reduced because of 6% bentonite in foamed glass(29)		
Fire Resistance	Assumed similar to P.C.	Non-combustible outstanding (18)	Perlite, fire resistant (18)

^b Any lightweight has an insulation value approximately four times greater than ordinary concrete.

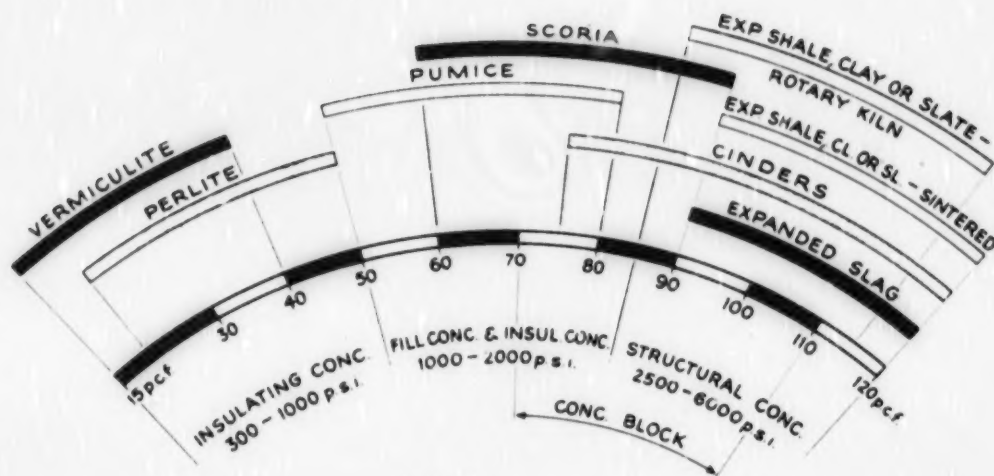


Figure 28. WEIGHT SPECTRUM OF LIGHTWEIGHT CONCRETES*

*Source: Lightweight Concrete--History, Applications, Economics.
Washington, D.C.: Expanded Shale Clay and Slate Institute, 1971.

C. Characteristics of Foamed Waste Glass as Rigid Insulation

Rigid insulation is insulation which is self-supporting and holds its shape. Rigid foamed glass insulation is characterized by good strength characteristics, water resistance, almost perfect resistance to the migration of moisture and poor abrasion resistance. It may be produced in blocks, boards, molded, or cut to a shape.

The wood fiber insulation board commonly used in residential construction has a thermal conductivity lower than foamed glass.⁽¹⁹⁾ In situations where vapor barriers are unnecessary, this gives an advantageous position to the wood fiber insulation. It is normal to install a vapor barrier between the ambient conditions and the insulated object because of the intrusion of moisture into insulation which would increase the conductivity.

The best vapor barriers available are blocks of cellular material. With the exception of cellular (foamed) glass, all rigid cellular insulations will either transmit liquid water or water vapor.⁽¹⁸⁾ Foamed glass only requires sealing at the joints because foam glass does not absorb moisture and is completely impervious to vapors, having a permeability rating of 0.00.⁽²⁴⁾ This vapor barrier also acts as a barrier to rodents and vermin which is especially important in cold storage units.

One of the physical properties of foamed glass which limits its use⁽¹⁹⁾ is the melting point. The foam is initially created at 700° - 800° C. Therefore, the use of foamed glass is limited to lower temperatures. When it is desirable to use foamed glass with objects of higher temperatures to create a vapor barrier, an intermediate high temperature insulation is used between the high temperature object and the foamed glass.

The concrete spectrum shows the relative weights and differing applications of the various lightweight aggregates now in use. At the extreme left are concretes using vermiculite and perlite, which are sometimes referred to as the "super lightweights". Concrete can be made with these aggregates weighing as little as 15 or 20 pounds per cubic foot.

Next are the natural aggregates, pumice and scoria. These can be made into concrete weighing about 25 or 30 pounds, and it also may run as high as 65 pounds per cubic foot. Overlapping these are concretes using coal cinders, with a range from 75 to 120 pounds, and expanded shale, clay and slate aggregates. Beyond the natural aggregates are aggregates such as sand and gravel and crushed stone, which produce conventional concretes weighing 135 to 150 pounds per cubic foot.

Some of the physical characteristics of foamed glass and other products are listed in Table 16. A comparison of these characteristics indicates that perlite, vermiculite and foamed glass are very similar. The prime consideration is the density of the aggregate which determines the density and strength of the concrete. The density of foamed glass is about the same range as perlite density. The density could be extended to higher values by less foaming if this were desired.

J. Craig Phillips of the Riverside Cement Company, Riverside, California, indicates in his research that glass in concrete and specifically masonry block seems feasible because there is a lack of significant glass water reaction.^(22,23) He also indicates that although there is a slight decrease in strength at 18 months the blocks continued to show a good strength trend. After the 18-month time period, the test blocks,

which had been cured in high humidity to encourage a glass cement reaction, exceeded the strength of normal, yard-cured blocks. It is assumed that if crushed glass has such good results when used in concrete then foamed glass will also maintain similar properties. The foamed glass at the University of Utah also contains bentonite which retards the reaction of glass with water and this should decrease any potential reactions.

Tests using glass in concrete have shown that test values are within the American Society for Testing Materials (ASTM) code specification. The tests were run using crushed glass in concrete rather than foamed glass.^(22,30) The tests met the ASTM compressive strength and linear expansion tests.

The use of lightweight aggregate in masonry blocks permits increased labor productivity because the decreased weight makes for greater speed and ease of handling. Similar considerations apply in the case of pre-cast elements using lightweight structural concrete. However, there are decreases in compressive strength which accompany lighter weights.

The foamed glass could be used in either a foamed bead or crushed block form. The crushed block would provide a rougher bonding surface but the bead provides a greater ease of handling.⁽¹⁵⁾

D. The Market Potential for Lightweight Concrete Aggregate

Density is the critical variable in determining the use of concrete and makes it possible to divide the concrete aggregate market into three basic categories according to the density characteristics of the product. The density requirements of various concrete products have important implications for the potential of foamed waste glass as a lightweight concrete aggregate due to the difficulty of producing high density foamed glass.

This important production restriction effectively eliminates foamed waste glass from the structural concrete market (except possibly for use in concrete blocks) because concrete used for such purposes must have high density characteristics to provide adequate structural strength. The market for foamed waste glass is further reduced by the competitive price disadvantage of foamed waste glass with respect to pumice and scoria. The price per short ton of pumice or scoria in 1974 was \$2.23 compared to \$66-\$93 a short ton for foamed waste glass. It is obvious that only in those cases or regions where pumice and scoria are unavailable will there be any opportunity to capture a share of this market.

This means the market for foamed glass as a lightweight aggregate is limited to insulation concrete which is dominated by two super lightweight aggregates--vermiculite and perlite. Both of these lightweight aggregates require high transportation costs which limits the extent of their markets. These transportation costs make entry into the market attractive, particularly in those areas currently located long distances from a lightweight aggregate source. Such conditions obviously offer the most favorable circumstances for market entry but it should be emphasized that foamed waste glass is also competitive in those market areas located near a vermiculite or perlite source. For example, Utah Lumber Company, a Salt Lake firm, is an expander of vermiculite and supplies most of the state with the product at approximately \$17.50 a cubic foot. Foamed waste glass can be produced at a price which would be very competitive provided the other barriers to market entry are surmountable.

Table 17 shows the number of short tons of vermiculite and perlite used as lightweight aggregates in the United States from 1969-1973. The data in these tables shows that the lightweight aggregate market has been

Table 17
Light Weight Concrete Aggregate Market for Vermiculite and Perlite
(short tons)

Year	Vermiculite	Perlite	Total
1969	110,000	108,500	218,500
1970	88,000	79,000	167,000
1971	84,000	77,000	161,000
1972	104,000	84,200	188,200
1973	137,000	75,200	212,200

Source: U.S. Department of the Interior, *Minerals Yearbook*, Volume I, 1969-1973 (Washington, D.C.: U.S. Government Printing Office).

Table 18
Value of Light Weight Aggregate Market

Year	Vermiculite (dollar./ton)	Perlite (dollars/ton)	Total Value (millions of dollars)
1969	\$ 79.66	\$54.95	\$14.8
1970	85.11	60.00	12.3
1971	99.93	60.07	12.6
1972	100.31	60.17	15.0
1973	106.44	67.02	19.6

Source: U.S. Department of the Interior, *Minerals Yearbook*, Volume I, 1969-1973 (Washington, D.C.: U.S. Government Printing Office).

very cyclical, being heavily influenced by non-residential construction. Nevertheless, the lightweight aggregate industry is optimistic about its future. The energy crisis and the high cost of fuels have forced energy conservation measures on the building industry leading to a rising demand for improved techniques and methods of insulation. It is against the backdrop of the energy crisis that the excellent insulation properties of lightweight concrete are expected to provide expanding markets for the industry. The data in these tables do not show any recent dramatic increases in the use of lightweight aggregates to verify the industry's optimism but industry spokesmen do agree that 1975 data will show an increase in the use of lightweight aggregates for insulation concrete. Of course, any foamed glass producers would benefit from increased demand for lightweight aggregates for insulation concrete.

The barriers to entry of lightweight aggregate industry for foamed waste glass are not severe. There are no significant advantages in economies of scale that would give established firms a competitive advantage, nor is there significant product differentiation or cost advantage for established firms. Perhaps the largest barrier to entry would be "product loyalty" for the vermiculite and perlite products. Nevertheless, entry of foamed waste glass into the lightweight aggregate market seems possible, but there are some important considerations about the nature of this market which should be discussed to properly assess the potential of foamed waste glass as a lightweight aggregate.

The data in Tables 17 and 18 show the total national market in 1973 of 212,240 short tons for lightweight concrete aggregates, valued at \$19,600,000. Given the price and product similarities of foamed waste glass to lightweight concrete aggregates, foamed waste glass should be

able to capture some part of the lightweight aggregate market, but it should be stressed that the lightweight aggregate market is a very small market. Five foamed waste glass plants each producing 20 tons of foamed glass pellets per day would need to capture 10 percent of the current lightweight aggregate market to be profitable. The total value of this penetration of foamed waste glass into the lightweight aggregate market would be only \$2 million and represents production of 21,000 tons of foamed waste glass pellets.

The demand for foamed glass in the eleven state western region was examined to get a better understanding of the structure of the lightweight aggregate market.

In 1974 the non-residential construction industry in this region was valued at \$6.3 billion. Of this \$6.3 billion valuation, only \$6.2 million was spent on lightweight concrete aggregates. This is a dramatic illustration of the limited market for lightweight concrete aggregates. It is this limited market which will require a foamed waste glass plant to capture a significant share of the lightweight concrete aggregate market if the operation is to be profitable.

For instance, in the eleven state western region, a 20/ton/day foamed waste glass plant would produce 7,300 tons of foamed waste glass pellets a year. Priced at \$80 a ton this production level means a total output value of \$584,000. Assuming a market capture rate of 10 percent the lightweight concrete aggregate market in the eleven western states would be sufficient to sustain only one 20/ton/day foamed waste glass plant.

The small market for lightweight concrete aggregates would require a foamed waste glass plant to broaden its market and produce slab-foamed waste glass for rigid insulation purposes.

Table 19 and 20 give regional and national market demand data.

Table 19

Western Market for Lightweight Concrete Aggregate
(millions of dollars)

Year	Total Value Non-Resid. Construction	Total Value of Concrete	Total Value of Concrete Aggregate	Total Value of Lightweight Concrete Aggregate	Value of 10% of the Lightweight Concrete Aggregate Mkt.	No. of 20 Ton/Day Plants Rqd.
1971	\$4,051.5	\$121.6	\$24.3	\$3.9	\$.390	.7
1972	4,770.7	143.1	28.6	4.6	.460	.8
1973	5,980.9	179.4	35.9	5.7	.570	1.0
1974	6,271.9	188.2	37.6	6.0	.600	1.0
1975	5,822.9 ^a	174.7	34.9	5.6	.560	1.0

Table 20

National Market for Lightweight Concentrate Aggregate
(millions of dollars)

Year	Total Value Non-Resid. Construction	Total Value of Concrete	Total Value of Concrete Aggregate	Total Value of Lightweight Concrete Aggregate	Value of 10% of the Lightweight Concrete Aggregate Mkt.	No. of 20 Ton/Day Plants Rqd.
1971	\$25,590.2	\$ 767.7	\$153.5	\$24.5	\$2.45	4.2
1972	27,118.9	813.6	162.7	26.0	2.60	4.5
1973	31,761.4	952.8	190.1	30.4	3.04	5.2
1974	33,859.5	1,015.8	203.2	32.5	3.25	5.6
1975	30,336.3 ^a	910.1 ^b	182.0 ^c	29.1 ^d	2.91	5.0 ^e

(Source and Footnotes apply to both Table 19 and Table 20.)

Source: Compiled by Bureau of Economic and Business Research, University of Utah, Salt Lake City, Utah, 1976.

^aMcGraw-Hill, *Building Cost Calculator and Valuation Guide* (New York, New York: McGraw-Hill Information Systems Company) 1976.

^bMcGraw-Hill, *1976 Dodge Construction System Costs* (New York, New York: McGraw-Hill Information Systems Company) 1976. From this source it was determined that 3% of the cost of non-residential construction was the cost of concrete.

^c20% of the cost of concrete is the cost of aggregate.

^dU.S. Department of the Interior, *Minerals Yearbook*, Volume 1, 1969-1973 (Washington, D.C.: U.S. Government Printing Office).

^eDetermined by dividing value of annual production of a 20 ton/day plant into value of 10% of lightweight concrete aggregate market.

E. Plant and Production Costs

Plant and production costs for slab production are determined for four different daily outputs of 10, 20, 30 and 40 tons per day. A summary of the cost for these plants is shown in Table 21.

A 20 percent rate of return on investment (before taxes) requires that the foamed waste glass slabs be sold at \$.10 per board foot for the 10/ton/day plant and \$.065 per board foot for the 40/ton/day plant.

Since the selling price of the commercially available cellular foam glass is approximately \$.24 per board foot, it appears that the method of foaming waste glass as presented in this report is highly competitive with other similar products.

Plant and production cost for pellet production is determined for plants producing 10 and 40/tons/day of foamed pellets, Table 22.

Table 21

Cost of Production Summary - Slab Production

	<u>Plant A</u>	<u>Plant B</u>	<u>Plant C</u>	<u>Plant D</u>
Daily Output (tons/day)	10	20	30	40
Annual Output (bdft/year)	7,000,000	14,000,000	21,000,000	28,000,000
Total Capital Costs	\$ 1,217,590	\$ 1,662,540	\$ 2,058,370	\$ 2,625,240
Annual Operating Costs	\$ 452,420	\$ 747,250	\$ 1,030,540	\$ 1,331,900
Cost per board foot	\$.06463	\$.05337	\$.04908	\$.04757

Table 22

Cost of Production Summary - Pellet Production

	<u>Plant A</u>	<u>Plant B</u>
Daily Output (tons/day)	10	40
Annual Output (lbs/year)	7,000,000	28,000,000
Total Capital Costs	\$ 637,500	\$ 1,142,330
Annual Operating Costs	\$ 326,310	\$ 923,980
Costs per Pound	\$.04661	\$.03297

The market prices derived from the above tables were adjusted for inflation when used in the regional and national demand calculations.

IX. SLAB PRODUCTION

Plant and production costs are estimated for four different production levels of 10, 20, 30 and 40/tons/day. The final size of the slabs are 18 inches by 24 inches by 3 inches.

A. Capital Cost

The capital cost estimate is of the general type called a "study estimate" by Weaver, et al.⁽³²⁾ This type of estimate, prepared from a flow chart and a minimum of equipment data, can be expected to be within 30 percent of the actual cost. Major items of equipment for the various production levels are listed in Table 23. Table 24 shows the equipment and plant costs. Factors for foundations, piping, instruments, etc., covers additional costs for installation.^(14,20) Estimates for some equipment such as the kiln include installation costs.

The field indirect, which covers field supervision, inspection, temporary construction, equipment rental, and payroll overhead is estimated at 10 percent of the direct cost. Engineering, and administrative and overhead are each estimated at 5 percent of total construction cost. A contingency allowance of 10 percent and a contractor's fee of 5 percent are also included.

Plant facilities and plant utilities are estimated at 1 percent of the plant cost. Start-up cost equals total operating cost for one month. Working capital is defined as the funds in addition to fixed capital, land investment and start-up costs that must be provided to operate the plant. Working capital is estimated from the following items: (1) raw materials inventory (cost of raw materials for one month), (2) product

Table 23
Major Items of Equipment - Slab Production

Item	Quantity	Description	Quantity	Description
Hopper	1	6' x 4'	1	6' x 4'
Jaw Crusher	1	15" x 18" opening	1	15" x 18" opening
Storage bins (CaCO ₃) (bentonite) (ground glass)	1	3' diameter x 7' high	1	5' diameter x 6' high
	1	6' diameter x 9' high	1	8' diameter x 8' high
	1	7' diameter x 9' high	1	8' diameter x 10' high
Conveyor belts	2	14" x 12'	2	14" x 12'
Impact grinder and classifier with compressor, dust collector, fan, etc.	1	6000 lbs/hr	1	6000 lbs/hr
Extruder	1	17" diameter ave, 325 hp	1	17" diameter ave, 325 hp
Pre-kiln cutter	1	20" guillotine cutter	1	20" guillotine cutter
Dryer	1	85' long, 16 car capacity	1	128' long, 24 car capacity
Tunnel kiln	1	85' long, 8 car capacity	1	128' long, 12 car capacity
Kiln cars	82	5' x 10'	75	7' x 10'
Post-kiln cutter	1	5" x 18" maximum cross-section	1	5" x 18" maximum cross-section
Packager	1	strapping machine	1	strapping machine
Front-end loader	1	18 ft ³ capacity	1-	18 ft ³ capacity

Table 23 (Continued)

Major Items of Equipment - Slab Production

Item	Quantity	Description	Quantity	Description
		30 tons/day	40 tons/day	
Hopper	1	6' x 4'	1	6' x 4'
Jaw Crusher	1	15" x 18" opening	1	15" x 18" opening
Storage Bins (CaCO ₃) (bentonite) (ground glass)	1	5' diameter x 8' high	1	6' diameter x 8' high
	1	8' diameter x 10' high	1	8' diameter x 12' high
	1	8' diameter x 14' high	1	8' diameter x 18' high
Conveyor belts	2	14" x 12'	2	14" x 12'
Impact grinder and classifier with compressor, dust collector, fan, etc.	1	6000 lbs/hr	1	6000 lbs/hr
Extruder	1	17" diameter ave, 325 hp	1	17" diameter ave, 325 hp
Pre-kiln cutter	1	20" guillotine cutter	1	20" guillotine cutter
Dryer	1	156' long, 30 car capacity	1	128' long, 24 car capacity
Tunnel kiln	1	156' long, 15 car capacity	1	128' long, 12 car capacity
Kiln cars	75	8' x 10'	105	7' x 10'
Post-kiln cutter	1	5" x 18" maximum cross-section	1	5" x 18" maximum cross-section
Packager	1	strapping machine	1	strapping machine
Front-end loader	1	18 ft ³ capacity	1	18 ft ³ capacity

Table 24

Equipment and Plant Cost Summary - Slab Production

	10 tons/day			20 tons/day		
	Cost	Labor	Total	Cost	Labor	Total
Hopper	\$ 1,400	\$ 60	\$ 1,460	\$ 1,400	\$ 60	\$ 1,460
Jaw crusher	3,000	400	3,400	3,000	400	3,400
Storage bins (3)	2,000	100	2,100	3,000	150	3,150
Conveyor belts (2)	4,600	800	5,400	4,600	800	5,400
Impact grinder and classifier	46,000	500	46,500	46,000	500	46,500
Compressor, dust collector, fan, etc.	39,000	500	39,500	39,000	500	39,500
Extruder	53,000	500	53,500	53,000	500	53,500
Pre-kiln cutter	6,000	300	6,300	6,000	300	6,300
Dryer			40,000			70,000
Tunnel kiln			127,500			192,000
Kiln cars and trackage			63,460			63,460
Post-kiln cutter	40,000	500	40,500	40,000	500	40,500
Packager			200			200
Forklift - truck and manual			11,260			11,260
Trucks - open bed and dump truck			22,000			25,000
Front-end loader			7,000			7,000
TOTAL	\$ 195,000	\$ 3,660	\$ 470,000	\$ 196,000	\$ 3,710	\$ 576,830
Building			\$ 220,700			\$ 347,400
Land			6,000			8,000
TOTAL			\$ 696,700			\$ 932,230

Table 24 (Continued)

	10 tons/day	20 tons/day
	Total	Total
Equipment cost x factor indicated		
Foundations .05	\$ 9,750	\$ 9,800
Structures .04	7,800	7,840
Electrical .03	5,850	5,880
Painting .01	1,950	1,960
Instrumentation .01	1,950	1,960
Piping .03	5,850	5,880
Subtotal	\$ 33,150	\$ 33,320
TOTAL DIRECT COSTS	\$ 729,930	\$ 965,550
Field Indirect - 10% of Total Direct Costs	72,990	96,550
TOTAL CONSTRUCTION COSTS	\$ 802,920	\$ 1,062,100
Engineering 5% of Total Construction Costs	\$ 40,150	\$ 53,100
Administration Overhead - 5% Construction Costs	40,150	53,100
Subtotal	883,220	\$ 1,168,300
Contingency - 10% of above subtotal	88,320	\$ 116,830
Subtotal	\$ 971,540	\$ 1,285,130
Contractor Fee - 5% of above subtotal	\$ 48,580	\$ 64,260
TOTAL COST	\$ 1,020,120	\$ 1,349,390

Table 24 (Continued)

	30 tons/day	40 tons/day
	Total	Total
Equipment cost x factor indicated		
Foundations .05	\$ 9,860	\$ 9,900
Structures .04	7,890	7,920
Electrical .03	5,920	5,940
Painting .01	1,970	1,980
Instrumentation .01	1,970	1,980
Piping .03	5,920	5,940
Subtotal	\$ 33,530	\$ 33,660
TOTAL DIRECT COSTS	\$ 1,165,540	\$ 1,481,160
Field Indirect - 10% of Total Direct Costs	\$ 116,550	\$ 148,120
TOTAL CONSTRUCTION COSTS	\$ 1,282,090	\$ 1,629,280
Engineering - 5% of Total Construction Costs	\$ 64,100	\$ 81,460
Administration Overhead - 5% Construction Costs	64,100	81,640
Subtotal	\$ 1,410,290	\$ 1,792,200
Contingency - 10% of above subtotal	\$ 141,030	\$ 179,220
Subtotal	\$ 1,551,320	\$ 1,971,420
Contractor Fee - 5% of above subtotal	\$ 77,570	\$ 98,570
TOTAL COST	\$ 1,628,890	\$ 2,069,990

Table 24 (Continued)

Equipment and Plant Cost Summary - Slab Production

	30 tons/day			40 tons/day		
	Cost	Labor	Total	Cost	Labor	Total
Hopper	\$ 1,400	\$ 60	\$ 1,460	\$ 1,400	\$ 60	\$ 1,460
Jaw crusher	3,000	400	3,400	3,000	400	3,400
Storage bins (3)	4,200	200	4,400	5,000	250	5,250
Conveyor belts (2)	4,600	800	5,400	4,600	800	5,400
Impact grinder and classifier	46,000	500	46,500	46,500	500	46,500
Compressor, dust collector, fan, etc.	39,000	500	39,500	39,000	500	39,500
Extruder	53,000	500	53,500	53,000	500	53,000
Pre-kiln cutter	6,000	300	6,300	6,000	300	6,300
Dryer			92,000			122,500
Tunnel kiln			229,500			384,000
Kiln cars and trackage			85,290			100,330
Post-kiln cutter	40,000	500	40,500	40,000	500	40,500
Packager			200			200
Forklift - truck and manual			11,260			11,260
Trucks - open bed and dump truck			38,000			41,000
Front-end loader			7,000			7,000
TOTAL	\$ 197,200	\$ 3,760	\$ 664,210	\$ 198,000	\$ 3,810	\$ 868,100
Building			\$ 457,800			\$ 567,400
Land			10,000			12,000
TOTAL			\$1,132,010			\$ 1,447,500

and in-process inventory (total operating cost for one month), (3) accounts receivable (total operating cost for one month), and (4) available cash (direct expenses for one month, table #25).

B. Operating Costs

The estimated operating costs (Table 26) are based on 350 days of operation per year, which allows 15 days for inspection, maintenance, and unscheduled interruptions. These costs are divided into direct, indirect, and fixed costs.

Direct costs include raw materials, packaging costs, utilities, labor, maintenance, payroll overhead, and operating supplies. Direct labor requirements are shown in Table 27. Supervisory costs are estimated at 12 percent of the labor costs. Payroll overhead includes vacations, social security, and fringe benefits.

Indirect costs are estimated at 30 percent of direct labor and maintenance. It includes the expenses of accounting, plant protection and safety, plant administration, and company overhead. Fixed cost includes property taxes, insurance, and depreciation. Depreciation is based on a straight-line, 15-year period.

Table 25

Estimated Capital Cost - Slab Production

	10 tons/day	20 tons/day	30 tons/day	40 tons/day
Fixed Capital:				
Equipment and Plant Cost	\$ 1,020,120	\$ 1,349,390	\$ 1,628,890	\$ 2,069,990
Start-Up Cost	33,420	45,730	63,300	81,600
Plant Facilities	20,400	26,990	32,580	41,400
Plant Utilities	20,400	26,990	32,580	41,400
Fixed Capital Cost	\$ 1,094,340	\$ 1,449,100	\$ 1,757,350	\$ 2,234,390
Working Capital:				
Raw Materials	\$ 3,670	\$ 7,350	\$ 11,030	\$ 14,710
Product In-Process Inventory	63,240	108,440	152,230	197,160
Accounts Receivable	31,620	54,220	76,120	98,580
Available Cash	24,720	43,430	61,640	80,400
Working Capital Costs	\$ 123,250	\$ 213,440	\$ 301,020	\$ 390,850
Total Capital Costs	\$ 1,217,590	\$ 1,662,540	\$ 2,058,370	\$ 2,625,240

Table 26

Estimated Annual Operating Costs - Slab Production

	10 tons/day		20 tons/day	
	Annual Costs	Cost/board foot	Annual Costs	Cost/board foot
Direct Cost:				
Raw Materials:				
Glass at \$12/ton	\$ 42,000	.600 ¢	\$ 84,000	.600 ¢
Bentonite at \$6/ton	1,050	.015	2,100	.015
CaCO ₃ at \$30/ton	1,070	.015	2,130	.015
TOTAL	\$ 44,120	.630 ¢	\$ 88,230	.630 ¢
Packaging Materials	\$ 50,920	.727 ¢	\$ 101,840	.727 ¢
TOTAL	\$ 50,920	.727 ¢	\$ 101,840	.727 ¢
Utilities				
Natural Gas at \$.35/MCF	\$ 5,000	.071 ¢	\$ 10,000	.071 ¢
Electric Power at \$.015/kwhr				
Grinding	6,150	.088	12,300	.088
Other equipment	3,000	.043	6,000	.043
TOTAL	\$ 14,150	.202 ¢	\$ 28,300	.202 ¢
Direct Labor				
Labor at \$3.35/hour	\$ 78,400	1.120 ¢	\$ 135,100	.965 ¢
Supervision at 12% of labor	9,410	.134	16,200	.116
TOTAL	\$ 87,810	1.254 ¢	\$ 151,300	1.081 ¢
Plant Maintenance				
Labor at \$3.35/hour	\$ 14,000	.200 ¢	\$ 17,500	.125 ¢
Materials	25,320	.362	34,060	.243
TOTAL	\$ 39,320	.562 ¢	\$ 51,560	.368 ¢

Table 26 (Continued)
Estimated Annual Operating Costs - Slab Production

	30 tons/day		40 tons/day	
	Annual Costs	Cost/board foot	Annual Costs	Cost/board foot
Direct Cost:				
Raw Materials:				
Glass at \$12/ton	\$ 126,000	.600 €	\$ 168,000	.600 €
Bentonite at \$6/ton	3,150	.015	4,200	.015
CaCO ₃ at \$30/ton	3,200	.015	4,270	.015
TOTAL	\$ 132,350	.630 €	\$ 176,470	.630 €
Packaging Materials	\$ 153,760	.727 €	\$ 203,680	.727 €
TOTAL	\$ 153,760	.727 €	\$ 203,680	.727 €
Utilities				
Natural Gas at \$.35/MCF	\$ 15,000	.071 €	\$ 20,000	.071 €
Electric Power at \$.015/kwhr				
Grinding	18,450	.088	24,600	.088
Other Equipment	9,000	.043	12,000	.043
TOTAL	\$ 42,450	.202 €	\$ 56,600	.202 €
Direct Labor				
Labor at \$3.35/hour	\$ 188,300	.896 €	\$ 239,400	.855 €
Supervision at 12% of labor	22,600	.108	28,730	.102
TOTAL	\$ 210,900	1.004 €	\$ 268,130	.957 €
Plant Maintenance				
Labor at \$3.25/hour	\$ 21,000	.100 €	\$ 24,500	.087 €
Materials	41,450	.197	54,770	.196
TOTAL	\$ 62,450	.297 €	\$ 79,270	.283 €

Table 26 (Continued)

	10 tons/day		20 tons/day	
	Annual Costs	Cost/board foot	Annual Costs	Cost/board foot
Direct Cost: (cont)				
Payroll overhead - 25% of payroll	\$ 25,450	.364 ¢	\$ 42,200	.301 ¢
Operating supplies - 20% of plant maintenance	7,860	.112	10,310	.074
TOTAL	\$ 33,310	.476 ¢	\$ 52,510	.375 ¢
Subtotal	\$ 269,630	3.852 ¢	\$ 437,740	3.384 ¢
Miscellaneous costs - 10% of above subtotal	\$ 26,960	.385 ¢	\$ 47,370	.338 ¢
TOTAL DIRECT COSTS	\$ 296,590	4.237 ¢	\$ 521,110	3.722 ¢
Indirect Costs - 30% of Direct Labor and Maintenance	\$ 38,740	.553 ¢	\$ 60,860	.435 ¢
Marketing expense - 8% of Direct Cost	23,730	.339	41,690	.298
TOTAL	\$ 359,060	5.129 ¢	\$ 623,660	4.455 ¢
Fixed Cost				
Taxes - 1.0% of Total Plant Cost	\$ 10,200	.146 ¢	\$ 13,490	.096 ¢
Insurance, 1.0% of Total Plant Cost	10,200	.146	13,490	.096
VARIABLE COSTS	\$ 379,460	5.420 ¢	\$ 650,640	4.647 ¢
Depreciation - 15 year life	\$ 72,960	1.042 ¢	\$ 96,610	.690 ¢
TOTAL OPERATING COSTS	\$ 452,420	6.463 ¢	\$ 747,250	5.337 ¢

Table 26 (Continued)

	30 tons/day		40 tons/day	
	Annual Costs	Cost/board foot	Annual Costs	Cost/board foot
Direct Costs: (cont)				
Payroll Overhead - 25% of payroll	\$ 57,980	.276 ¢	\$ 73,160	.261 ¢
Operating Supplies - 20% of plant Maintenance				
TOTAL	12,490	.059	15,850	.057
Subtotal	\$ 70,470	.335 ¢	\$ 89,010	.318 ¢
Miscellaneous costs - 10% of above subtotal	\$ 572,380	3.202 ¢	\$ 873,160	3.118 ¢
TOTAL DIRECT COSTS	\$ 67,240	.320 ¢	\$ 87,320	.312 ¢
	\$ 739,620	3.522 ¢	\$ 960,480	3.430 ¢
Indirect Costs - 30% of Direct Labor and Maintenance	\$ 82,010	.391 ¢	\$ 104,220	.372 ¢
Marketing expense - 8% of Direct Cost	59,170	.282	76,840	.274
TOTAL	\$ 880,800	4.194 ¢	\$ 1,141,540	4.077 ¢
Fixed Cost				
Taxes - 1.0% of Total Plant Cost	\$ 16,290	.078 ¢	\$ 20,700	.074 ¢
Insurance, 1.0% of Total Plant Cost	16,290	.078	20,700	.074
VARIABLE COSTS	\$ 913,380	4.349 ¢	\$ 1,182,940	4.225 ¢
Depreciation - 15 year life	\$ 117,160	.558 ¢	\$ 148,960	.532 ¢
TOTAL OPERATING COSTS	\$ 1,030,540	4.908 ¢	\$ 1,331,900	4.757 ¢

Table 27
Direct Labor Requirements - Slab Production

	10 tons/day			20 tons/day			30 tons/day			40 tons/day		
	Shift per Day	Days per Week	Total Men	Shift per Day	Days per Week	Total Men	Shift per Day	Days per Week	Total Men	Shift per Day	Days per Week	Total Men
Raw Materials Handling	1	5	1.0	2	5	1.5	3	5	2.0	3	7	2.5
Grinding Equipment	1	5	1.0	2	5	1.5	3	5	2.0	3	7	2.5
Dryer and Kiln	3	7	4.2	3	7	6.3	3	7	7.9	3	7	9.2
Car Loading and Unloading	1	5	2.0	2	5	4.0	3	5	6.0	3	7	8.0
Post - Kiln Cutter	1	5	1.0	2	5	2.0	3	5	3.0	3	7	4.0
Packager	1	5	1.0	2	5	2.0	3	5	3.0	3	7	4.0
Warehouse	1	5	1.0	2	5	2.0	3	5	3.0	3	7	4.0
Total			11.2			19.3			26.9			34.2

X. PELLET PRODUCTION

Plant and production costs are estimated for two different production levels of 10 and 40/tons/day. The foamed pellet size ranges from $\frac{1}{4}$ inch to $\frac{5}{8}$ inch in diameter. The capital and operating costs are estimated using the same method as described in Appendix A. Major items of equipment are listed in Table 28. The plant and total capital costs are tabulated in Tables 29 and 30. Annual operating costs are shown for the two plant sizes in Table 31. Direct labor requirements are shown in Table 32. Supervision is estimated at 18 percent of labor cost.

Table 28
Major Items of Equipment - Pellet Production

Item	Quantity		Description	Quantity		Description
	10 tons/day			40 tons/day		
Hopper	1	6' x 4'		1	6' x 4'	
Jaw crusher	1	15" x 18" opening		1	15" x 18" opening	
Storage bins	1	6' diameter x 9' high		1	8' diameter x 12' high	
	1	7' diameter x 9' high		1	8' diameter x 18' high	
Conveyor belts	3	14" x 12'		3	14" x 12'	
Impact grinder and classifier with compressor, dust collector, fan, etc.	1	6000 lbs/hr		1	6000 lbs/hr	
Extruder	1	6" ave.		1	6" ave.	
Rotary dryer	1	2' I D x 25' long		1	4' I D x 30' long	
Rotary kiln and pollution control equipment	1	2' I D x 25' long		1	4' I D x 30' long	
Packager	1	3 ft ³ bags		1	3 ft ³ bags	
Front-end loader	1	18 ft ³ capacity		1	18 ft ³ capacity	

Table 29
Equipment and Plant Cost Summary - Pellet Production

	10 tons/day			40 tons/day		
	Cost	Labor	Total	Cost	Labor	Total
Hopper	\$ 1,400	\$ 60	\$ 1,460	\$ 1,400	\$ 60	\$ 1,460
Jaw crusher	3,000	400	3,400	3,000	400	3,400
Storage bins (2)	3,000	200	3,200	3,000	200	3,200
Conveyor belts (3)	6,900	1,200	8,100	6,900	1,200	8,100
Impact grinder and classifier	46,000	500	46,500	46,000	500	46,500
Compressor, dust collector, fan, etc.	39,000	500	39,500	39,000	500	39,500
Extruder	7,500	500	8,000	7,500	500	8,000
Rotary dryer	15,000	1,500	16,500	22,500	2,000	24,500
Rotary kiln	30,000	3,500	33,500	45,000	4,500	49,500
Pollution control equipment	10,000	500	10,500	15,000	800	15,800
Packager	2,500	100	2,600	2,500	100	2,600
Forklifts - truck and manual			11,260			11,260
Trucks - open bed and dump truck			22,000			40,000
Front-end loader			7,000			7,000
TOTAL	\$ 164,300	\$ 8,960	\$ 213,520	\$ 191,800	\$10,760	\$ 260,820
Building			\$ 127,700			\$ 290,600
Land			6,000			10,000
TOTAL			\$ 133,700			\$ 561,420

Table 29 (Continued)

	10 tons/day	40 tons/day
	Total	Total
Equipment cost x factor indicated		
Foundations .05	\$ 8,220	\$ 9,590
Structures .04	6,570	7,670
Electrical .03	4,930	5,750
Painting .01	1,640	1,920
Instrumentation .01	1,640	1,920
Piping .03	4,930	5,750
Subtotal	\$ 27,930	\$ 32,600
TOTAL DIRECT COSTS	\$ 375,150	\$ 594,020
Field Indirect - 10% of Total Direct Costs	\$ 37,520	\$ 59,400
TOTAL CONSTRUCTION COSTS	\$ 412,670	\$ 653,420
Engineering - 5% of Total Construction Costs	\$ 20,630	\$ 32,670
Administration Overhead - 5% Construction Costs	20,630	32,670
Subtotal	\$ 453,930	\$ 718,760
Contingency - 10% of above subtotal	\$ 45,390	\$ 71,880
Subtotal	\$ 499,320	\$ 790,640
Contractor Fee - 5% of above subtotal	\$ 24,970	\$ 39,530
TOTAL COST	\$ 524,290	\$ 830,170

Table 30

Estimated Capital Cost - Pellet Production

	10 tons/day	40 tons/day
Fixed Capital:		
Equipment and Plant Cost	\$ 524,290	\$ 830,170
Start-up Cost	21,270	60,750
Plant Facilities	10,490	16,600
Plant Utilities	10,490	16,600
Fixed Capital Cost	\$ 566,540	\$ 924,120
Working Capital		
Raw Materials	\$ 3,670	\$ 14,710
Product In-Process Inventory	24,050	71,860
Accounts Receivable	24,050	71,860
Available Cash	19,260	59,780
Working Capital Cost	\$ 71,030	\$ 218,210
Total Capital Cost	\$ 637,570	\$1,142,330

Table 31
Estimated Annual Operating Costs - Pellet Production

	10 tons/day		40 tons/day	
	Annual Costs	Cost/board foot	Annual Costs	Cost/board foot
Direct Cost:				
Raw Materials:				
Glass at \$12/ton	\$ 42,000	.600 €	\$ 168,000	.600 €
Bentonite at \$6/ton	1,050	.015	4,200	.015
CaCO ₃ at \$30/ton	1,070	.015	4,270	.015
TOTAL	\$ 44,120	.630 €	\$ 176,470	.630 €
Packaging Materials	\$ 33,340	.476 €	\$ 133,360	.476 €
TOTAL	\$ 33,340	.476 €	\$ 133,360	.476 €
Utilities				
Natural gas at \$.35/MCF	\$ 2,500	.036 €	\$ 10,000	.036 €
Electric power at \$.015/kwhr				
Grinding	6,150	.088	24,600	.088
Other equipment	3,000	.043	12,000	.043
TOTAL	\$ 11,650	.167 €	\$ 46,600	.167 €
Direct Labor				
Labor at \$3.35/hour	\$ 57,400	.820 €	\$ 155,400	.820 €
Supervision at 18% of Labor	10,330	.148	27,970	.099
TOTAL	\$ 67,730	.968 €	\$ 183,370	.654 €
Plant Maintenance				
Labor at \$3.35/hour	\$ 14,000	.200 €	\$ 24,500	.087 €
Materials	13,320	.190	25,770	.092
TOTAL	\$ 27,320	.390 €	\$ 50,270	.179 €

Table 31 (Continued)

	10 tons/day		40 tons/day	
	Annual Costs	Cost/board foot	Annual Costs	Cost/board foot
Direct Costs: (cont)				
Payroll Overhead - 25% of payroll	\$ 20,430	.292 ¢	\$ 51,970	.186 ¢
Operating Supplies - 20% of Plant Maintenance	5,460	.078	10,050	.036
TOTAL	\$ 25,890	.370 ¢	\$ 62,020	.222 ¢
Subtotal	\$ 210,050	3.000 ¢	\$ 652,090	2.329 ¢
Miscellaneous costs - 10% of above subtotal	\$ 21,010	.300 ¢	\$ 65,210	.233 ¢
TOTAL	\$ 231,060	3.300 ¢	\$ 717,300	2.562 ¢
Indirect Costs - 30% of Direct Labor and Maintenance	\$ 28,520	.407 ¢	\$ 70,090	.250 ¢
Marketing Expense	18,480	.264	57,380	.205
TOTAL	\$ 278,060	3.971 ¢	\$ 844,770	3.017 ¢
Fixed Cost				
Taxes - 1.0% of Total Plant Cost	\$ 5,240	.075 ¢	\$ 8,300	.030 ¢
Insurance - 1.0% of Total Plant Cost	5,240	.075	8,300	.030
VARIABLE COSTS	\$ 288,540	4.121 ¢	\$ 862,370	3.077 ¢
Depreciation - 15 year life	\$ 37,770	.540 ¢	\$ 61,610	.220 ¢
TOTAL OPERATING COSTS	\$ 326,310	4.661 ¢	\$ 923,980	3.297 ¢

Table 32

Direct Labor Requirements - Pellet Production

	10 tons/day			40 tons/day		
	Shifts	Days per Week	Total Men	Shifts	Days per Week	Total Men
Raw Materials Handling	1	5	1.0	3	7	2.5
Grinding Equipment	1	5	1.0	3	7	2.5
Dryer and Kiln	3	7	4.2	3	7	9.2
Packager	1	5	1.0	3	7	4.0
Warehouse	1	5	1.0	3	7	4.0
Total			8.2			22.2

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